COMPETITION IN NETWORK INDUSTRIES: EVIDENCE FROM MOBILE TELECOMMUNICATIONS IN RWANDA

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This paper develops a method to analyze the effects of competition policy in a network industry. Competition has mixed effects on incentives to invest: when a network is split between competitors, each captures only a fraction of potential network effects. However, a firm may invest in components that are not shared, to attract customers to its network. I structurally estimate the utility of adopting a mobile phone from its subsequent usage, using transaction data from nearly the entire Rwandan network over 4.5 years. I simulate the equilibrium choices of consumers and network operators, and consider Rwanda's decision to delay the introduction of competition. Adding a competitor earlier would have reduced prices and in some cases *increased* incentives to invest in rural towers, increasing welfare by the equivalent of 1.4% of GDP. I analyze the effects of setting different interconnection rates, reducing switching costs through number portability, and introducing competition at different times in the evolution of the network.

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1. Introduction

Many modern technologies have network effects, and as a result lead to industries with natural monopolies (consider Facebook and Google; or in earlier eras, AT&T and Microsoft).[1] How should societies manage these industries?

Governments commonly intervene to spur competition, in the hope that consumer choice will discipline these industries. Governments can tilt the playing field by making it easier to switch, or by forcing an incumbent to connect its network to entrants (as in telecom, where regulations typically guarantee that consumers can call subscribers of competing networks). Or, governments can split up a dominant firm. However, if societies impose too much discipline, or exert discipline in the wrong ways, firms may not make the investments needed to build these networks.

This paper considers the effects of competition on investment and welfare in the context of mobile phone networks in sub-Saharan Africa. Although voice calls still account for the majority of revenues, in these societies mobile phone operators are emerging as gatekeepers to information services, the internet, and, increasingly, financial transactions.[2] The details of how to manage competition have been 'a main bottleneck' (World Bank, 2004), and regulators have little guidance on whether or how to tilt favor, allow consolidation (Moody's, 2015), or split firms (Reuters, 2017).[3]

There is little empirical work to guide policy in any industry with classical network effects, where each node's adoption directly affects the adoption decisions of other nodes.[4] While there is substantial theory on classical network goods, conclusions depend on empirical parameters.[5] Also, the theory on competition in developed

[1]As well as emerging networks like Uber, which some are betting will become the central network for coordinating urban transportation.

[2]Voice accounts for 60% of the my telecom partner's parent's African revenue in 2017 (including two small operations outside of Africa).

[3]The success of mobile money in Kenya (Suri et al., 2012; Bjorkegren and Grissen, 2018) has proven difficult to replicate: it may be that Safaricom made the large investments to scale M-PESA only because it had no effective competitors in the voice network.

[4]Most empirical work on classical network goods simply measures the extent of network effects; see for example Saloner and Shepard (1995), Goolsbee and Klenow (2002), and Tucker (2008). There is more work on markets with indirect network effects which tend to be more tractable, including platforms and video formats (Ohashi 2003; Gowrisankaran et al. 2010; relatedly, Lee 2013). In those markets, popular platforms tend to be better served by sellers, so adopters benefit indirectly from additional users.

[5]See Katz and Shapiro (1994) and Farrell and Klemperer (2007) for review articles.

country landline networks (Armstrong, 1998; Laffont et al., 1998; Laffont and Tirole, 2001) can be inconclusive (Vogelsang, 2013), and mostly omits factors important for growing networks such as investment and network effects in adoption.[6]

A reduced form approach would compare isolated networks in jurisdictions that set different policies. For example, Faccio and Zingales (2017) and Genakos et al. (2018) find that increases in telecom competition are associated with price reductions. However, firms choose prices and investments in anticipation of future policy. Depending on these expectations, a reduced form approach could suggest wildly different impacts of the same policy: a policy that lowers investment could appear to increase it, if firms anticipated that a more dramatic policy would be implemented. These firm expectations are typically unobservable. Even if this issue were overcome, there are too few isolated networks to assess the bewildering array of policy options.[7]

A structural approach that models firm objective functions faces three challenges. First, one needs to measure the entire network in order to capture spillover effects. As a result, it is typically not possible to study competitive markets directly: when a market is split, rich network data would need to be linked between all competitors.[8] Second, it is difficult to identify network effects, because each individual's demand is a function of the demand of others in the network. One individual may adopt after a contact adopts because the contact provides network benefits, or because connected individuals share similar traits or are exposed to similar environments. Finally, it is difficult to compute equilibria: firms must anticipate how the effects of an action ripple through the entire network of demand.

This paper overcomes these challenges in the context of Rwanda's mobile phone network. I evaluate the effects of tilting a network industry towards competition, using 5.3 billion transaction records from the incumbent mobile phone operator, which held over 88% of the market. I find that competition policies have enormous welfare

[6]With some exceptions (Valletti and Cambini, 2005).

[7]For example, Faccio and Zingales (2017) considers one dimensional indices of telecom competition policy, and finds statistically insignificant quality differences between countries with different levels of concentration, measured by coverage, speeds, capex ratios, or towers, controlling for GDP per capita, population, population density, and inflation rate.

[8]I am not aware of any studies that have linked network usage data from multiple competing networks.

consequences. Since my approach requires data only from an incumbent, it can be used by a regulator weighing policy options for an incumbent monopoly.

The Rwandan government initially limited competition to encourage investment in telecommunications. When Rwanda first allowed competition, it followed common practice: firms were not forced to share tower infrastructure, but were forced to interconnect so consumers could call across networks. I study a period of contested monopoly, which has three useful features. First, price varies: the incumbent lowered real calling prices by 76%. But—crucially—the entrant was poorly run and never attained significant market share, so the incumbent's data describes nearly the entire network at the time. Third, the incumbent made large investments in coverage, nearly quadrupling the number of towers and increasing coverage from 60% to 95% of land area.

After this period, the regulator granted an additional license to a well managed competitor, which built out less coverage, charged lower prices, and captured market share. What would have happened if this additional competitor had been granted a license earlier? Would the incumbent still have built coverage in rural areas?

I answer these questions using an empirical approach that has four parts:

First, acknowledging that the utility of owning a mobile phone is derived from its usage, I model the utility of using a phone, using the method and estimates of Bjorkegren (2018). Almost all phones in Rwanda are basic, prepaid mobile phones, and in the period I study mobile money did not exist.[9] I infer the value of each voice connection from subsequent interaction across that connection. This approach bypasses most of the simultaneity issues that result from inferring the value of links from correlations in adoption. Calls are billed on the margin, by the second, so a subscriber must value a connection at least as much as the cost of calls placed across it.[10] Variation in calling prices and the quality of coverage identify the underlying demand curve for communication across each link.

[9]Even as of this writing, only 9% of mobile phones in Rwanda are smartphones (ResearchICTAfrica, 2017).

[10]In the first 14 months of the data, calls are billed by the first minute and every following 30 seconds.

Second, I model the decision to adopt a mobile phone and operator. A phone provides utility by allowing communication with contacts that have phones. Consumers choose when to adopt by weighing the increasing stream of utility from communicating with the network against the declining cost of purchasing a handset.[11] I extend Bjorkegren (2018) to allow consumers to select and switch between operators, which may offer different price and coverage paths. I pose hypothetical questions to Rwandan consumers to estimate switching costs and idiosyncratic preferences for the entrant.[12]

Third, I model firm decisions. As a condition for receiving a license, the Rwandan regulator required firms to submit 5 year tower rollout plans. I require firms to commit to a rollout plan as well as a path of calling prices. To limit the multiplicity of equilibria, I require that firms charge the same rate for on- and off-network calls. These represent terms of competition that could be implemented; since the regulator may be able to do better under different terms, my results represent a lower bound of the potential welfare benefits of competition. To evaluate the cost of expanding or shrinking networks, I use engineering cost data collected under mandate by the regulator.

Fourth, to evaluate the impact of policies, I use an iterated best response algorithm to compute equilibria in a two stage game, where firms select price and rollout plans, and then consumers publicly announce adoption dates (the latter builds on Bjorkegren (2018)). I approximately bound the full set of equilibria by exploiting supermodularity in the adoption decision, in a manner similar to Jia (2008).

The resulting method can be used to evaluate the effect of a wide class of policies, including adding an entrant or breaking up the incumbent; changing the cost of switching operators; requiring networks to interconnect under different rates; directly regulating coverage or the price of calls; and changing taxes on handsets and airtime.

I allow an operator possessing the same parameters as the eventual entrant to enter in January 2005, and simulate the resulting firm and consumer adoption equilibria

[11]This approach has parallels with Ryan and Tucker (2012), which analyzes adoption of a videoconferencing system from its use. But in that context, individuals face no cost of use or adoption.
[12]I corroborate these estimates against an additional validation choice observed in my data, the choice of plan.

over the horizon through December 2008. I hold fixed the network and behavior of the poorly performing entrant.

I find the following:

At baseline the incumbent's mobile phone system provided net social welfare of $334-386m, an amount equivalent to 2-3% of Rwanda's GDP over the same period.

Adding a competitor under the government recommended interconnection rate would have dramatically lowered calling prices: the entrant would have charged 35% of the monopoly rate, and the incumbent 45%, earning a premium for its better coverage.

Adding a competitor would have also altered the incumbent's incentives to invest in rural towers. I quantify three forces. First, lowered prices reduce the total revenue generated from an investment in the 50 lowest revenue rural towers by 22-25%. Second, when the network is split but interconnected, some of the benefits spill across networks. 15-16% of the revenue from the incumbent's investment accrues to the entrant, holding fixed operator choices. The entrant pays the incumbent 10% back in interconnection fees, to account for increased usage of its network. In isolation, these two forces would make it unprofitable to build a substantial set of rural towers. However, because each firm offers its own tower infrastructure, there is a third effect, which in this case dominates. A business stealing effect accounts for 83-85% of the revenue the incumbent earns from building the rural network. Building out rural coverage allows the incumbent to attract the set of marginal urban subscribers who wish to use phones in rural areas but would otherwise subscribe to the lower priced operator. The balance of these forces depends on the interconnection rate; under the government's suggested rate, adding a competitor would have *increased* incentives to invest in rural towers.[13]

On net, adding a competitor under the government's suggested interconnection rates would have increased the net welfare provided by the mobile phone system by up to 60%, an amount equivalent to 1.4% of GDP or 6-7% of official development aid over this time period. This suggests that the industrial organization of emerging networks can have profound welfare implications for the world's poorest economies.

[13]These results are similar in flavor to Goettler and Gordon (2011), which finds that the effect of competition on investments in innovation can vary based on industry primitives.

Competition would have been unlikely to develop in absence of interconnection regulation, under these terms of competition. If the incumbent chose the terms of interconnection (and the regulator required operators to charge the same price for on- and off-net calls), the incumbent would have effectively blocked access to its network. This is reminiscent of many network industries that do not endogenously develop compatibility (Katz and Shapiro, 1985).

The particular rules that the regulator selects for the competitive environment can also have substantial welfare consequences. Lower interconnection rates tend to lower prices but also incentives to invest; different reasonable interconnection regimes produce differences in net social welfare equivalent to 0.3% of GDP over this period.

Switching costs have theoretically ambiguous effects on network competition (Farrell and Shapiro, 1988; Suleymanova and Wey, 2011; Chen, 2016). I find that a number portability policy would have shifted a small amount of subscribers and profits to the entrant and slightly increased welfare.

Finally, I show that allowing the entrant to enter near the end of this horizon greatly lessens its effects on the market.

To my knowledge, this represents the first empirical analysis of competing firms that accounts for classical network effects, using micro data. It builds on the network demand system developed in Bjorkegren (2018), which in that paper is used to assess the impact of taxes and a coverage requirement on a monopoly network. It is related to two papers that analyze how encouraging nodes to adopt affects the adoption of other nodes in a network: Ryan and Tucker (2012) for a corporate videoconferencing system (using transaction records), and Guiteras et al. (2018) for household latrines in Bangladesh (using an RCT).

My approach has two limitations. First, like a regulator in the position of deciding to handle a monopoly network, I do not observe network usage data from a period of effective competition. However, I am able discipline my models of firm and consumer behavior using other sources of data from Rwanda after the market became competitive, and from other markets that were competitive at the time. Second, the network is illuminated by usage, so individuals who do not adopt under baseline conditions are omitted. I model the behavior of nodes in this 'dark' portion of the network, and report results for shorter time horizons before these nodes would have adopted.

2. Context

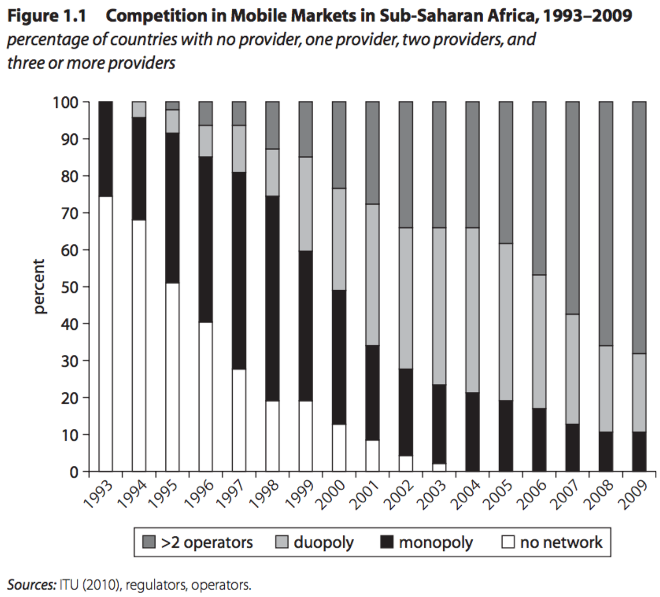
Developing country phone systems. Between 2000 and 2011, the number of mobile phone subscriptions in developing economies increased from 250 million to 4.5 billion (ITU, 2011). Handsets were initially expensive, but became accessible even to the poor as component costs decreased. (In 2005, the cheapest mainstream handset in Rwanda cost roughly \$70, or 3.5 months of the mean person's consumption; by 2009 handsets were available for \$13.) As poor consumers began to be able to afford phones, operators expanded coverage to increasingly remote regions.

As these networks grew, regulators quickly realized that it may be possible to obtain better performance from the sector by allowing multiple operators to compete in providing service. However, an entrant phone network will be of limited use unless it can connect to an existing phone system. Left to the market, incumbents typically demand prohibitively high fees for interconnection, preventing competition (the 'one way' access problem). Thus, regulators typically intervene and determine the terms of interconnection. When network sizes are balanced, theory suggests that the problem is lessened but ongoing regulation is required, since negotiated interconnection rates can be an instrument of collusion (the 'two way' access problem: Armstrong, 1998; Laffont et al., 1998). Theory suggests that interconnection rates be set to a function of the cost of connecting a phone call, and the World Bank (2004) model represents a benchmark. But different theoretical models suggest different optimal interconnection rates, and most telecom theory is designed for mature developed country networks, and does not consider how policies affect growth of the network.

Thus, developing societies face two large questions: how much competition should regulators promote? And how should regulators shape the competitive landscape?

After resolving initial interconnection disputes, most countries have slowly invited competition (see Figure 1), first over voice service and then over new services like data. But there have been increasing calls for consolidation; and in East Africa

Figure 1. Telecom Competition



Source: Williams et al. (2011)

between 2010 and 2015, only one country saw net entry of a telecom operator while three countries had net exit.

There is also little consensus on the optimal ground rules for competition. Table 1 summarizes the diversity of current industry statistics and regulations in sub-Saharan Africa. While most countries regulate retail and interconnection prices, they consider different information to determine levels, and allow different amounts of complexity.

Rwanda. In the aftermath of the genocide and civil war, the Rwandan government in 1998 granted a license to a multinational operator to develop and run a mobile phone system (Operator A); it was understood that this license would be exclusive for a limited period of time. Attached to the license was a requirement that the operator build out rural coverage.

In 2003, the government announced it would provide a license to a second operator, which entered the market in 2005 (Operator B). The second operator sought to connect its network to the first; the resulting dispute over interconnection was "the major problem" at the regulatory agency at the time (RURA, 2005, 2006). In 2006, a consultant was hired to implement the World Bank Long Run Incremental Cost

Table 1. Mobile Telecommunications in sub-Saharan Africa

Industry Statistics (2015 or latest available)	Mean	SD
Number of operators	3.27	1.48
Top market share	0.58	0.19
Second highest market share	0.32	0.09
Market concentration (HHI)	0.49	0.21
Regulations*		
Retail prices are regulated	89%	
...based on costs	43%	
...based on benchmarks	38%	
Interconnection charges are regulated	97%	
...based on costs (LRIC or FDC)	71%	
...based on benchmarks	43%	
...asymmetrically between operators	31%	
...using multiple zones	34%	
...using multiple timebands	56%	
Infrastructure is shared	100%	
...by mandate	62%	
...including active infrastructure (electronics)	48%	

Industry statistics from 2015 or latest year available, source: regulator reports and news articles.
*Regulation statistics from 2015, for all SSA countries with available regulatory data (ranges from 21 to 41 countries depending on question), source: ITU.

model. Despite the resolution of the interconnection dispute, this second operator was troubled and unsuccessful: after several changes in ownership (including by part of the Libyan government), it reached a maximum of 20% of market share for a brief period after the end of my data. In 2011, its license was revoked for failure to meet obligations.[14]

In an effort to push competition, the Rwandan regulator granted a license to a third operator (Operator C), which entered the market at the end of 2009 with aggressive prices.[15] This spurred a second interconnection dispute: the regulator again hired

[14]The Registrar General, Louise Kanyonga said, "The company was mismanaged and their liabilities far outweigh their assets... This has been a real learning experience for our government. We need to ask how this happened."

[15]The Rwandan government sought to avoid duplication of infrastructure and in 2011 required operators to share infrastructure at cost. This ex post sharing mandate allowed the new operator to

a consultant, who used detailed cost data from operators to recommend lowering interconnection rates along a glide path (see Argent and Pogorelsky, 2011; PwC, 2011; RURA, 2009).

In 2011 a license was granted to Operator D, which purchased the assets of Operator B. In 2018, Operator C and D merged, bringing the market back to a duopoly.

See Figure 2 for the evolution of handset prices, accounts, calling prices, and coverage. The coverage plot shows that despite being able to build on the incumbent's towers, entrants' networks offer less complete coverage.

This paper uses data from the period 2005-2009. The calling price plot shows the baseline calling price, and foreshadows the result of a focal counterfactual where Operator C is granted a license in 2005 at the analyst recommended interconnection rate of \$0.07 per minute.

Consumer choice. The ability of competition to discipline firms depends on how consumers choose between them. Table 2 shows the results of a Research ICT Africa survey of phone owners in several sub-Saharan African countries.

In Rwanda, almost all phone plans are prepaid.[16] Handsets are standard, imported models; local prices track global trends. Most are purchased from independent sellers: operator handset sales records account for only 10% of total handsets activated during the period of my data. I consider the handset market as perfectly competitive, with availability and prices unaffected by the market for cellular service.

During this period, phones were used primarily for voice calls. Mobile money did not exist in Rwanda. I do not explicitly model utility from SMS, missed calls, international calls, and calls from payphones.[17] Any value these omissions provide will be captured in a residual when I estimate the adoption decision.

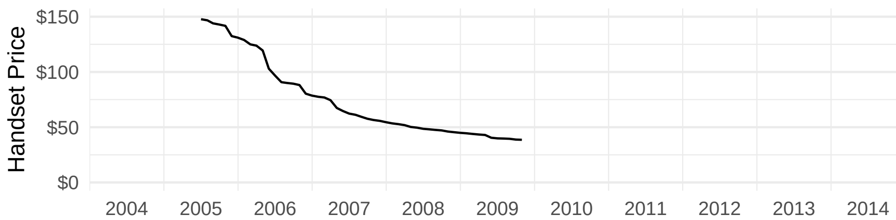
quickly expand its network, but Operator A expressed concerns that it could chill future investment. (The government used a new, ex-ante sharing model for the next major infrastructure investment: it granted a license to a South Korean firm to build a single, wholesale 4G network, which was leased out to the operators.) In my simulations I do not apply the infrastructure sharing mandate.

[16]In 2007-8, no surveyed phone owners received their handset with a contract.

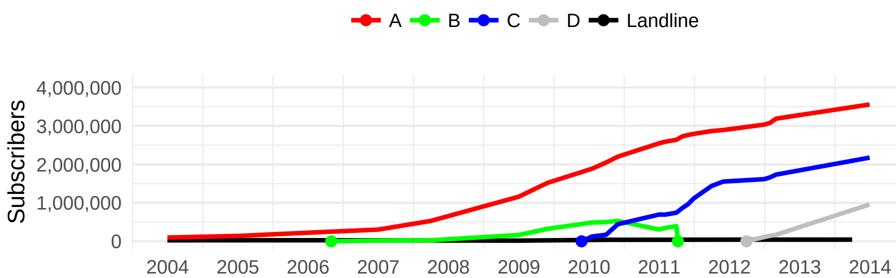
[17]From the data it is not possible to match the sender and receiver of a given SMS. Though important in other contexts, in Rwanda text messaging or SMS was high priced (\$0.10 per message) and represented less than 13% of revenue and 16% of transactions. Only calls that are answered incur a charge; so subscribers may communicate simple information with missed calls (Donner, 2007). But it is difficult to distinguish between missed calls that provide utility (communicating information) and those that provide disutility (due to network problems or inability to connect).

FIGURE 2. Development of Telecommunications in Rwanda

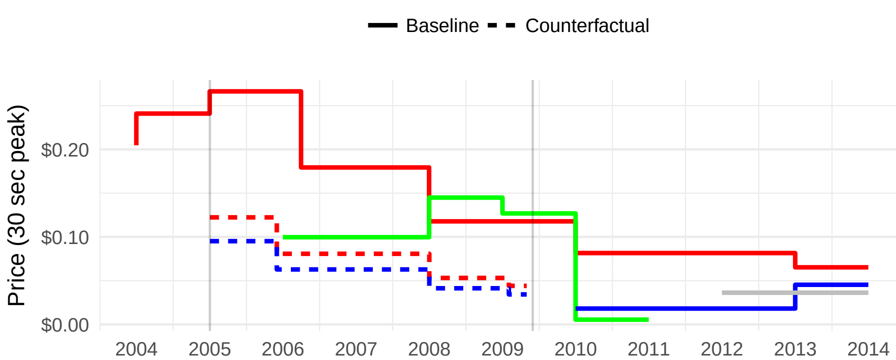
(a) Handset Price (real, quality adjusted index)



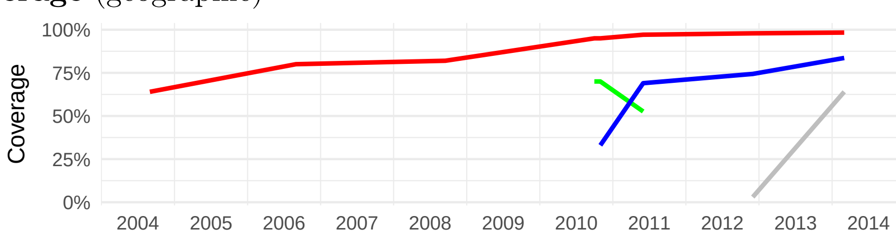
(b) Accounts



(c) Calling Price, On Network (30 second, nominal)



(d) Coverage (geographic)



Handset prices reported during the years I have data on prices and quantities. I report baseline calling prices and the prices from a focal counterfactual where Operator C enters in 2005 with an interconnection rate of $0.07 per minute. Sources: archived operator websites and regulator reports.

Table 2. Mobile Phone Usage among Owners in sub-Saharan Africa

	2007-8		2010-11	
	Rwanda	SSA**	Rwanda	SSA*
Received phone with a contract	0%	3%	3%	11%
Use phone for				
Voice calls	95%	98%	100%	99%
Music or radio	6%	14%	35%	46%
Taking photos or videos	5%	15%	24%	39%
Email	2%	3%	13%	14%
Sending or receiving money	-	-	18%	18%
Browsing Internet	-	-	15%	17%
Facebook or other social network	-	-	14%	16%
Apps (downloaded)	-	-	6%	15%

Source: RIA household surveys 2007-2008 and 2010-2011. *: Representative samples of mobile phone owners in Cameroon, Ethiopia, Ghana, Kenya, Mozambique, Namibia, Nigeria, Rwanda, South Africa, Tanzania, and Uganda; **: also Benin, Botswana, Burkina Faso, Cote d'Ivoire, Senegal, and Zambia. A dash indicates that question was not asked in that survey round.

Consumers report selecting operators mostly based on coverage (51% of respondents, multiple responses allowed), which network their contacts are on (37%), the range of services offered (27%), and price (20%).[18] I develop a model to capture the key differentiators (coverage and pricing).

3. Data

This project uses several data sources (for more information see Supplemental Appendix):

Call detail records: As a side effect of providing service, mobile phone operators record data about each transaction, called Call Detail Records (CDRs). This project uses anonymous call records from the dominant Rwandan operator, which held above 88% of the market during this period. This data includes nearly every call, SMS, and top up made over 4.5 years by the operator's mobile phone subscribers, numbering approximately 400,000 in January 2005 and growing to 1.5 million in May 2009. For each transaction, the data reports: anonymous identifiers for sender and receiver,

[18] See Supplemental Appendix: Operator Differentiators.

corresponding to the phone number and handset, time stamps, the location of the cell towers used, and call duration.[19] I aggregate durations to the monthly level.

Operator costs: Following common practice, the Rwandan regulator regularly collects cost data from operators in order to ensure interconnection rates are 'derived from relevant costs' (RURA, 2009). I use long run incremental costs from a study conducted for Rwanda by international consultants (PwC, 2011), which was crosschecked against regional and international benchmarks.

Coverage: A rollout plan, $\mathbf{z} = \{(t_z, x_z, y_z)\}_z$, is defined by tower build dates and geographical coordinates. I consider the baseline rollout, $\mathbf{z}_{full}$, as well as counterfactual rollouts that trim low revenue rural towers. I create coverage maps by computing the areas within line of sight of the towers operational in each month, a method suggested by the operator's network engineer. Elevation maps are derived from satellite imagery recorded by NASA (Jarvis et al., 2008; Farr et al., 2007).

Individual locations and coverage: Because handsets are mobile, an individual may make calls from several locations, such as a village and the capital. I infer the geographical coordinates of each subscriber i's set of most used locations, $\{(x_{il}, y_{il})\}_l$, based on their eventual calls, using an algorithm analogous to triangulation (a version of Isaacman et al. (2011) that I have modified to improve performance in rural areas). Because individuals may use the phone in the area surrounding each location, I compute a smoothed coverage map, where $\phi_t(x, y; \mathbf{z})$ represents an average of the coverage available near (x, y) under rollout plan $\mathbf{z}$, weighted by a two-dimensional Gaussian kernel with radius 2.25km. I compute an individual specific coverage sequence by taking the average of the coverage at each individual's important locations weighted by the days spent at each location, d_{il}: $\phi_{it}(\mathbf{z}) = \frac{\sum_l \phi_t(x_{il}, y_{il}; \mathbf{z}) \cdot d_{il}}{\sum_l d_{il}}$.

Handset prices: I create a monthly handset price index $p_t^{handset}$ based on 160 popular models in Rwanda, adjusting for quality and weighting each model by the quantity activated on the network.

[19]Some months of data are missing; from the call records: May 2005, February 2009, and part of March 2009. The locations of 12% of tower identifiers are missing from this data; I infer their location based on call handoffs with known towers using a procedure I have developed (Bjorkegren, 2014).

Consumer survey: I fielded a small consumer survey in Rwanda in the summer of 2017, to determine how consumers select between mobile phone operators in a competitive market.

4. Model

In this section I develop a model of handset adoption and usage, extended from Bjorkegren (2018) to allow for competition. Since the utility of owning a phone is derived from making calls, I begin in reverse, with a model of usage.

Consumers. Let $\bar{G}$ be the communication graph of Rwanda (a directed social network), with N nodes representing all individuals in the country. A directed link $ij \in \bar{G}$ indicates that i would have a potential desire to call j via phone. I assume that links are fixed.

Let $S_t \subseteq N$ be the set of individuals with phones in month t. Since I observe only individuals who adopt by the end of my data T, I observe the set $S_T \subseteq N$. This omits the small number of individuals who subscribed to the incumbent's first competitor, less than 12% of the market; I assume that these individuals' usage remains the same in any counterfactual.[20] It also omits any other 'dark' nodes $i \in N \backslash S_T$ who may have adopted if conditions were more favorable. Since I only observe a link if a call was placed, I observe the subgraph, $G^T \subseteq \bar{G}$, where $ij \in G^T$ if i has called j by period T.[21] As shorthand, define $G_i = \left\{ j \left| ij \in G^T \right. \right\}$ as i's set of contacts. I report simulation results for shorter time horizons $\tilde{T} \leq T$, during which the omission of dark nodes would not affect results.

In estimation and baseline simulations, each individual $i \in S_T$ may select only the incumbent operator ($a_{it} = 0$). For convenience, I will refer to this baseline market structure as monopoly. In counterfactuals, each individual $i \in S_T$ may select either the incumbent or the new entrant ($a_{it} \in \{0, 1\}$).

[20] This may result in underestimating the effects of competition. Operator B used CDMA, a technology incompatible with the other GSM networks, and thus it would have been costly for individuals to switch. In my data I do not observe calls between Operators A and B.

[21] This will miss any links between subscribers where there is a latent desire to communicate but no call has been placed by T ($G^T \subseteq \bar{G}^T$). See Supplemental Appendix.

Calling decision. Operators are interconnected, so in each period t that individual i has a phone, he can call any contact j that subscribes to either operator, $j \in G_i \cap S_t$. i draws a communication shock $\epsilon_{ijt} \overset{iid}{\sim} F_{ij}$ representing a desire to call j, and chooses a total duration $d_{ijt} \geq 0$ for that month, earning utility:

$$u_{ijt} = \max_{d_{ijt} \geq 0} \left[\frac{1}{\beta_{cost}} v_{ij}(d, \epsilon_{ijt}) - c_{ijt} d \right] \tag{1}$$

where $v(d, \epsilon)$ represents the benefit of making calls of total duration of d, c_{ijt} represents the per-second cost, and β_{cost} corresponds to a coefficient on price (which converts between utils and money).

I model the benefit of making calls as:

$$v_{ij}(d, \epsilon) = d - \frac{1}{\epsilon} \left[\frac{d^\gamma}{\gamma} + \alpha d \right]$$

where the first term represents a linear benefit; $\gamma > 1$ controls how quickly marginal returns decline, and α controls the intercept of marginal utility, and thus the fraction of months for which no call is placed.[22]

The marginal cost of placing a call is affected by the choice of operator:

$$c_{ijt} = p_t^{a_{it} a_{jt}} + \beta_{coverage} \phi_{it}^{a_{it}} \phi_{jt}^{a_{jt}}$$

where $p_t^{a_{it} a_{jt}}$ is the per-second calling price for a call from firm a_{it} to a_{jt} (including any tax). $\beta_{coverage} \phi_{it}^{a_{it}} \phi_{jt}^{a_{jt}}$ represents the hassle cost when the caller or receiver have imperfect coverage. An individual's coverage $\phi_{it}^a \in [0, 1]$ is derived from the fraction of the area surrounding his most used locations receiving cellular coverage in month t under firm a's rollout plan.

The benefit of an additional second of duration across a link is decreasing, so i will call j until the marginal benefit equals the marginal cost, at duration:

$$d(\epsilon, \mathbf{p}_t, \phi_{it}, \phi_{jt}, \mathbf{a}) = \left[\epsilon \left(1 - \beta_{cost} (p_t^{a_{it} a_{jt}} - \beta_{coverage} \phi_{it}^{a_{it}} \phi_{jt}^{a_{jt}}) \right) - \alpha \right]^{\frac{1}{\gamma - 1}} \tag{2}$$

which increases with the desire to communicate (ϵ) and decreases with cost. $\mathbf{p}_t$ represents the vector of prices by firm, $\boldsymbol{\phi}_t$ represents the vector of coverage by individual and firm, and $\mathbf{a}$ represents firm choices for each individual. If the desire

[22] This functional form was chosen to satisfy 8 reasonable properties for the utility from telephone calls; see Bjorkegren (2018).

to communicate is not strong enough, i does not call: $d_{ijt} = 0$ when $\epsilon_{ijt} \leq \underline{\epsilon}_{ijt} := \frac{\alpha}{1-\beta_{cost}\left(p_t^{a_{it}a_{jt}} - \beta_{coverage}\phi_{it}^{a_{it}}\phi_{jt}^{a_{jt}}\right)}$.

Then, calls from i to j in period t have expected duration:

$$Ed_{ij}(\mathbf{p}_t, \boldsymbol{\phi}_t, \mathbf{a}) = \int_{\underline{\epsilon}_{ijt}}^{\infty} d(\epsilon, \mathbf{p}_t, \boldsymbol{\phi}_t, \mathbf{a}) \cdot dF_{ij}(\epsilon)$$

and provide expected utility:

$$Eu_{ij}(\mathbf{p}_t, \boldsymbol{\phi}_t, \mathbf{a}) = \int_{\underline{\epsilon}_{ijt}}^{\infty} \left[d(\epsilon, \mathbf{p}_t, \boldsymbol{\phi}_t, \mathbf{a}) \cdot \left(\frac{1}{\beta_{cost}} \left(1 - \frac{\alpha}{\epsilon} \right) - p_t^{a_{it}a_{jt}} - \beta_{coverage}\phi_{it}^{a_{it}}\phi_{jt}^{a_{jt}} \right) - \frac{1}{\beta_{cost}\epsilon} \frac{d(\epsilon, p_t, \boldsymbol{\phi}_t, \mathbf{a})^{\gamma}}{\gamma} \right] dF_{ij}(\epsilon)$$

If they are valued, incoming calls provide utility:

$$E\tilde{u}_{ji}(\mathbf{p}_t, \boldsymbol{\phi}_t, \mathbf{a}) = \int_{\underline{\epsilon}_{jit}}^{\infty} \left[d(\epsilon, \mathbf{p}_t, \boldsymbol{\phi}_t, \mathbf{a}) \cdot \left(\frac{1}{\beta_{cost}} \left(1 - \frac{\alpha}{\epsilon} \right) - \beta_{coverage}\phi_{it}^{a_{it}}\phi_{jt}^{a_{jt}} \right) - \frac{1}{\beta_{cost}\epsilon} \frac{d(\epsilon, p_t, \boldsymbol{\phi}_t, \mathbf{a})^{\gamma}}{\gamma} \right] dF_{ji}(\epsilon)$$

Altogether, each month i uses operator a_{it}, he receives actual expected utility from each contact who has also adopted:

(3)
$$Eu_{it}(\mathbf{p}_t, \boldsymbol{\phi}_t, \mathbf{a}, \boldsymbol{x}_{G_i}) = \sum_{j \in G_i \text{ and } x_j \leq t} \left[Eu_{ij}(\mathbf{p}_t, \boldsymbol{\phi}_t, \mathbf{a}) + w \cdot E\tilde{u}_{ji}(\mathbf{p}_t, \boldsymbol{\phi}_t, \mathbf{a}) \right] - s \cdot 1_{\{a_{it} \neq a_{it-1}\}}$$

where x_j represents j's adoption time, $w \in [0, 1]$ specifies whether recipients value incoming calls, and s represents the cost of switching operators.[23]

However, at the point of adoption, i anticipates that having a phone in month t will provide utility:

$$E\hat{u}_{it}(\mathbf{p}_t, \boldsymbol{\phi}_t, \mathbf{a}, \boldsymbol{x}_{G_i}) = Eu_{it}(\mathbf{p}_t, \boldsymbol{\phi}_t, \mathbf{a}, \boldsymbol{x}_{G_i}) + \eta_i^{a_{it}}(1 - \delta)$$

where an individual's type (η_i^0, η_i^1) represents heterogeneity in the anticipated utility of using a phone on each operator that is unobserved to the econometrician. Types need not be mean zero, but to make simulation tractable I do require that each individual's type is constant over time and across counterfactuals. Each month that i does not have a phone he receives utility zero.

[23]This would include the cost of changing accounts (swapping SIM cards and adjusting any settings), and notifying contacts about the change in phone number.

Adoption decision. Conditional on the adoption decisions of others, an individual's adoption decision is an optimal stopping problem. At period t, i knows the current price of a handset, $p_t^{handset}$ (inclusive of any tax). He believes his contacts will adopt at times $\boldsymbol{x}_{G_i}$ using operator sequences $\mathbf{a}_{G_i}$, and that in period $x > t$, the handset price will be $E_t p_x^{handset}$, a deterministic function that is described in the following section. He expects the utility of adopting at time x with operator sequence $\mathbf{a}_i$ to be:

$$(4) \qquad E_t U_i^{\mathbf{a}_i,x}(\mathbf{p}, \boldsymbol{\phi}, \boldsymbol{x}_{G_i}, \mathbf{a}_{G_i}) = \delta^x \left[\sum_{s \geq x}^{\infty} \delta^{s-x} E\hat{u}_{is}(\mathbf{p}_s, \boldsymbol{\phi}_s, \mathbf{a}, \boldsymbol{x}_{G_i}) - E_t p_x^{handset} \right]$$

i adopts in the first month x_i where he expects adopting immediately to be more attractive than waiting, given his beliefs about contacts' adoptions:

$$(5) \qquad \min\ x_i\ s.t. \left[\max_{\mathbf{a}_i} E_{x_i} U_i^{\mathbf{a}_i,x_i}(\mathbf{p}, \boldsymbol{\phi}, \boldsymbol{x}_{G_i}, \mathbf{a}_{G_i}) \geq \max_{s > x_i, \tilde{\mathbf{a}}_i} E_{x_i} U_i^{\tilde{\mathbf{a}}_i,s}(\mathbf{p}, \boldsymbol{\phi}, \boldsymbol{x}_{G_i}, \mathbf{a}_{G_i}) \right]$$

and selects operator sequence $\mathbf{a}_i$ to maximize utility. In counterfactuals, I allow consumers to delay adoption beyond the end point of the data $\bar{T} > T$, but report outcomes only up to a shorter horizon $\tilde{T} \leq T$.

Consumer surplus. The expected net present value of consumer surplus through $\tilde{T}$ is given by:

$$U_{net}^{\tilde{T}} = \sum_{i \in S_T \text{ and } x_i \leq \tilde{T}} \left[\sum_{t \geq x_i}^{\tilde{T}} \delta^t E u_{it}(\mathbf{p}_t, \boldsymbol{\phi}_t, \mathbf{a}, \boldsymbol{x}_{G_i}) - \left(\delta^{x_i} p_{x_i}^{handset} - \delta^{\tilde{T}} p_{\tilde{T}}^{handset} \right) \right]$$

which is net of calling, handset, and hassle costs. I assume handsets are provided by a competitive market at marginal cost, and are sold back at the end of the horizon at the prevailing price.[24]

Firms. Each firm F commits to a path of calling prices $\mathbf{p}^F$ and a tower building plan $\mathbf{z}^F$ through horizon $\tilde{T}$. Although in practice firms would make decisions anticipating the full stream of profits into the future, my data has an end date, so I assume firms maximize net present profits through horizon $\tilde{T}$:[25]

$$\pi_F^{\tilde{T}}(\mathbf{p}, \boldsymbol{z}, \mathbf{a}, \mathbf{x}, \boldsymbol{f}) = R_F^{\tilde{T}}(\mathbf{p}, \boldsymbol{z}, \mathbf{a}, \mathbf{x}, \boldsymbol{f}) - C_F^{\tilde{T}}(\mathbf{p}, \boldsymbol{z}, \mathbf{a}, \mathbf{x})$$

[24]This will underestimate consumer surplus if given conditions (prices $\mathbf{p}$, coverage $\boldsymbol{\phi}$, and adoption $\mathbf{a}$ and $\boldsymbol{x}$), any dark nodes ($i \in N \backslash S_T$) or latent links ($ij \in \bar{G} \backslash G^T$) became active before $\tilde{T}$.
[25]As a result, firms neglect the value of their stock of subscribers at $\tilde{T}$. In the Supplemental Appendix I find that results to not differ substantially under different choices of $\tilde{T}$.

Firm F earns revenue from the calls of their own subscribers and from interconnection fees charged to the competitor's subscribers who call in to the network:

$$R_F^{\tilde{T}}(\mathbf{p}, \boldsymbol{z}, \mathbf{a}, \mathbf{x}, \boldsymbol{f}) = \sum_{i \in S_T} \sum_{t \geq x_i}^{\tilde{T}} \delta^t \sum_{j \in G_i \cap S_t} Ed_{ij}(\mathbf{p}_t, \boldsymbol{\phi}_t(\mathbf{z}), \mathbf{a}) \cdot \left[\overbrace{(1 - \tau_{it}^{usage}) p_t^{a_{it} a_{jt}} \cdot 1_{\{a_{it}=F\}}}^{\text{Subscribers}} + \underbrace{f_{ij} \left[1_{\{a_{it} \neq F \cap a_{jt}=F\}} - 1_{\{a_{it}=F \cap a_{jt} \neq F\}} \right]}_{\text{Interconnection}} \right]$$

where $\boldsymbol{\phi}_t(\mathbf{z})$ is the coverage provided at time t under the rollout plans $\mathbf{z} = \{\mathbf{z}^0, \mathbf{z}^1\}$, τ_{it}^{usage} represents the airtime tax rate, and f_{ij} is the interconnection rate.

Firm F incurs costs:

$$\begin{aligned} C_F^{\tilde{T}}(\mathbf{p}, \boldsymbol{z}, \mathbf{a}, \mathbf{x}) &= K_{rural} \cdot \sum_{z \in \mathbf{z}^F, z \text{ is off grid}} \sum_{t \geq x_z}^{\tilde{T}} \delta^t \\ &+ \sum_{i \in S_T} \sum_{t \geq x_i}^{\tilde{T}} \delta^t \sum_{j \in G_i \cap S_t} Ed_{ij}(\mathbf{p}_t, \boldsymbol{\phi}_t(\mathbf{z}), \mathbf{a}) \cdot (ic_{L_i, onnet_{ij}}^{out} \cdot 1_{\{a_{it}=F\}} + ic_{L_j, onnet_{ij}}^{in} 1_{\{a_{jt}=F\}}) \\ &+ \sum_{t \geq \min\{x_z | z \in \mathbf{z}^F\}}^{\tilde{T}} \delta^t \left(fc^F + lc^F \right) \end{aligned} \tag{6}$$

K_{rural} represents the annualized cost of owning and operating a rural tower.[26] $ic_{L_i, onnet_{ij}}^{direction}$ is the incremental cost of sending or receiving an additional second, including switching equipment, staff, central operations, and costs of capital. I allow the cost to vary by whether the two parties are on the same network, and whether each subscriber is primarily urban or rural ($L_i \in \{\text{urban}, \text{rural}\}$). Each month that its network is operational, operator F also incurs fixed cost fc^F and license fee lc^F regardless of the size of its operations.

Government. The government decides whether to grant a license to the entrant firm, and if so, decides how to set the interconnection policy f_{ij} and license fee lc^F. It earns revenue:

[26] I define a tower as urban if it covers Kigali or one of Rwanda's 5 largest towns; a subscriber is defined as urban if his most used tower is urban.

$$R_G^{\tilde{T}}(\mathbf{p}, \boldsymbol{z}, \mathbf{a}, \mathbf{x}) = \sum_{F \in \{0,1\}} \sum_{t \geq \min\{x_z | z \in \mathbf{z}^F\}}^{\tilde{T}} \delta^t lc^F +$$
$$\sum_{i \in S_T \text{ and } x_i \leq \tilde{T}} \left[\delta^{x_i} \tau_{ix_i}^{handset} p_{x_i}^{handset} + \sum_{t \geq x_i}^{\tilde{T}} \left(\delta^t \tau_{it}^{usage} \sum_{j \in G_i \cap S_t} p_t^{a_{it} a_{jt}} \cdot Ed_{ij}(\mathbf{p}_t, \boldsymbol{\phi}_t, \mathbf{a}) \right) \right]$$

This includes revenue from taxes on adoption ($\tau_{it}^{handset}$) and usage (τ_{it}^{usage}); I hold these fixed at Rwanda's rates at the time (48% tax on handsets and 23% tax on usage). I do not take a stand on whether the government maximizes welfare, revenue, or another objective.

Equilibrium. An equilibrium reconciles firm choices with the network of consumer choices. As a condition for receiving or renewing a license, regulators commonly require mobile telecoms to submit tower rollout plans; in Rwanda, these specify towers to be constructed over a horizon of 5 years.[27] To make simulation tractable, I assume the regulator requires firms to commit to a plan through $\tilde{T}$ that specifies tower rollout and also a path of prices.

At the beginning of time, the interconnection terms $\boldsymbol{f}$ are set, either by the incumbent (unregulated interconnection) or the government (regulated interconnection). Firms anticipate which equilibrium consumers will coordinate on. The game proceeds in two stages. In the first stage, firms simultaneously announce their price sequence $\mathbf{p}^F$ and tower construction plan $\mathbf{z}^F$. In the second stage, each individual considers operators' plans, and simultaneously announces their adoption date x_i and operator sequence $\mathbf{a}_i$. To account for numerical approximation error, I consider ε-equilibria in firm choices.

[27]These appear to be enforced: in 2007, Operator B was fined for failing to comply with its coverage and rollout plan.

More formally:

Given consumer types $\boldsymbol{\eta}$, interconnection terms $\boldsymbol{f}$, and horizon $\tilde{T}$, an ε-**equilibrium** $\boldsymbol{\Gamma}(\boldsymbol{\eta}, \boldsymbol{f}, \tilde{T})$ is a tuple $(\mathbf{p}^0, \mathbf{p}^1, \mathbf{z}^0, \mathbf{z}^1, \mathbf{a}, \mathbf{x})$ such that:

- $(\mathbf{x}, \mathbf{a})$ is a network adoption partial equilibrium given $(\mathbf{p}^0, \mathbf{p}^1, \mathbf{z}^0, \mathbf{z}^1)$
- Each firm F cannot profit more than ε by deviating from price sequence $\mathbf{p}^F$ and tower construction plan $\mathbf{z}^F$, given the competing firm's price sequence and tower construction plan, interconnection terms, and individual adoption dates and operator choices:

$$\pi_F^{\tilde{T}}(\mathbf{p}^F, \mathbf{p}^{-F}, \boldsymbol{z}^F, \boldsymbol{z}^{-F}, \mathbf{a}, \mathbf{x}, \boldsymbol{f}) \geq \pi_F^{\tilde{T}}(\tilde{\mathbf{p}}^F, \mathbf{p}^{-F}, \tilde{\boldsymbol{z}}^F, \boldsymbol{z}^{-F}, \mathbf{a}, \mathbf{x}, \boldsymbol{f}) - \varepsilon \text{ for all } \tilde{\mathbf{p}}^F \text{ and } \tilde{\mathbf{z}}^F$$

Given firm choices $(\mathbf{p}^0, \mathbf{p}^1, \mathbf{z}^0, \mathbf{z}^1)$ and a vector of consumer types $\boldsymbol{\eta}$, a **network adoption partial equilibrium** $(\mathbf{x}, \mathbf{a})$ is defined by adoption dates $\boldsymbol{x} = [x_i]_{i \in S_T}$ and operator choices $\mathbf{a} = [\mathbf{a}_i]_{i \in S_T}$ such that:

- Each initial adopter $i \in S_0$ selects operator sequence $\mathbf{a}_i \in \{0, 1\}^{\bar{T}}$ optimally according to Equation 5, with beliefs consistent with his contacts' decisions
- Every other observed adopter $i \in S_T \backslash S_0$ selects adoption date $x_i \in \{1, ..., \bar{T}\}$ and operator sequence $\mathbf{a}_i \in \{0, 1\}^{\bar{T} - x_i}$ optimally according to Equation 5, with beliefs consistent with his contacts' decisions

Expectations. Individuals correctly forecast call prices p_x, coverage $\boldsymbol{\phi}_x$, and their contacts' adoption dates $\boldsymbol{x}_{G_i}$, and operator choices $\mathbf{a}_{G_i}$. Because a handset becomes sunk at the time of purchase, forecasts of future prices can sway the adoption decision. I assume that at each period t, individuals learn the current handset price and expect the price in future periods to decline at an exponential rate consistent with the overall decline over this period:

$$E_t p_x^{handset} = \omega^{x-t} p_t^{handset}$$

for $\omega = \left(\frac{p_{\bar{T}}^{handset}}{p_0^{handset}} \right)^{\frac{1}{\bar{T}}}$.

Together, this notion corresponds to an equilibrium of a game where each individual adopts at the first sufficiently attractive date, based on the expected path of handset prices, and the actual decisions of contacts. It implies that individuals do not anticipate how later adopters will respond to their actions, because later adopters may not condition their strategy on actions in prior periods.[28] It also introduces a slight inconsistency: when i decides whether to adopt in period x_i, he does not know future handset prices, but does know the adoption dates and operator choices of his future contacts, which will have incorporated future handset prices. I tolerate this inconsistency in order to have a computable notion of equilibrium.

If at the point of adoption, an individual forecasts differently than specified here, the error will be captured in his type (η_i^0, η_i^1), as long as the error is fixed across time and counterfactuals.[29]

This notion allows for rich behavior: a perturbation of utility that causes one individual to change their adoption date can shift the equilibrium, inducing ripple effects through potentially the entire network. Firms internalize revenue from network effects in their own networks, but not from network effects that spill over into competing networks, except that partially recovered through interconnection fees.

5. Estimation

I combine estimates from a monopoly setting with additional parameters characterizing competitive choice, and supply side costs.

Consumer decisions when there is a single operator. Individuals choose when to adopt a mobile phone and, if they adopt, how to use the phone. The usage decision reveals the value of each connection, and how that value changes with prices and coverage. The adoption decision reveals any residual factors affecting adoption with the incumbent (individual type η_i^0). I use the estimation method and estimates of Bjorkegren (2018), described here.

Identification. Traditional approaches towards network goods estimate the value of each connection indirectly, based on correlations in adoption. For example, consider individual i who has one link, does not consider the future ($\delta = 0$), and is deciding whether to adopt, $A_i \in \{0, 1\}$. i will adopt if the value exceeds the cost:

$$A_i = I\left(\theta_{ij} A_j + \eta_i^0 \geq p_t^{handset}\right)$$

[28] This results in an open loop equilibrium; see for example Fudenberg and Levine (1988).

[29] To assess the importance of forward looking behavior, Bjorkegren (2018) also estimates and simulates results under a myopic model where individuals do not consider the future in their adoption decision, for the monopoly case. Results are similar in character.

where θ_{ij} is the value of the link if j also adopts. It is difficult to estimate θ_{ij} from correlations in adoption: each individual's adoption depends on the other's, as well as any unobserved shocks, which are likely to be correlated (Manski, 1993). Approaches that instrument for adoption tend to rely on very particular variation, and yield crude measures of value.[30]

Rather than inferring θ_{ij} from correlated adoption, I measure it directly. A link provides value because it enables calls:

$$\theta_{ij} = Eu_{ij}(p_t^0, \boldsymbol{\phi}_t^0)$$

I identify a link's value by how its usage changes in response to changes in the cost of communicating. The value of all links together represent the value of the network.

My approach requires that the latent desire to communicate (ϵ_{ijt}) is uncorrelated with costs (p_t^0 and $\phi_{it}^0\phi_{jt}^0$, which both improve over time). As the network grows, the composition of subscribers changes, and the operator may adjust prices and coverage in response. I absorb compositional changes by using only within-link variation to estimate the response of usage to costs. My identification assumption implies that the value of communicating with a particular contact does not otherwise trend over time, or depend on who else has adopted. I test this assumption by analyzing changes in calling patterns across links; results are consistent with these factors being negligible.[31] Apart from these restrictions, communication shocks can be arbitrarily correlated between any links in the network.

After the network portion of utility (θ_{ij}) is estimated, it is straightforward to back out any residual heterogeneity affecting adoption, η_i^0. These types may be arbitrarily correlated between nodes, but are fixed over time and across counterfactuals.

Call decision. Call decisions reveal the country's latent communication graph (the call shock distributions F_{ij}), the shape of the utility function (γ and α), and how

[30]For example, Tucker (2008) identifies the value of a videoconferencing system using variation in television watching partly driven by the World Cup. Instrumental variable approaches do not capture rich heterogeneity, or account for how the cost of using a link affects its value.

[31]I evaluate whether the duration of calls across a link changes with the time since an individual adopted, or as more of the sender's and receiver's contacts join the network, after controlling for cost. For the median subscriber, the change in duration associated with either the change in time and contacts on the network is less than 5% of the change associated with the changes in prices and coverage over this time period. See Supplemental Appendix.

usage responds to cost (β_{cost} and $\beta_{coverage}$). I allow the call shock distributions to vary at the link level $\epsilon_{ijt} \overset{iid}{\sim} F(\sigma_i, q_i, \mu_{ij})$ (an analogue of link fixed effects), so that the response of usage to cost is identified within-link (how does usage across a given link change as prices and coverage change). I specify the distribution for call shocks $\epsilon_{ijt} \overset{iid}{\sim} F_{ij}$ as a mixture distribution:

$$F_{ij}\left[\epsilon\right] = q_i \Phi\left(\frac{\ln\left(\epsilon\right) - \mu_{ij}}{\sigma_i}\right) + (1 - q_i) 1_{\{\epsilon > -\infty\}}$$

where $\Phi(\cdot)$ represents the standard normal CDF. The first component is a log-normal distribution, $\ln N(\mu_{ij}, \sigma_i^2)$, which captures a continuous spread of potential communication. It suggests that an individual will not call across a link if the shock is too low relative to the cost (affected by α in the utility function). However, on a given link, a large fraction of months have no calls. To better explain these I also include a point mass, under which there are no calls regardless of the cost (controlled by the individual parameter q_i).

In each period t, for each link between subscribers, I observe a duration $d_{ijt} \geq 0$. Equation 2 recovers the underlying call shock ϵ:

$$\epsilon\left(d, p_t, \phi_{it}, \phi_{jt}\right) = \frac{d^{\gamma-1} + \alpha}{1 - \beta_{cost}\left(p_t + \beta_{coverage}\phi_{it}\phi_{jt}\right)}$$

given coverage under the baseline rollout plan $\boldsymbol{\phi}_t(\mathbf{z}_0)$. If the call shock was not high enough to place a call of at least one second, the month will have no call ($d_{ijt} = 0$), with likelihood $F_{ij}\left[\epsilon\left(1 \text{ second}, \ldots\right)\right]$. The likelihood of calls of total duration d_{ijt} is $F_{ij}\left[\epsilon\left(d_{ijt} + 1, \ldots\right)\right] - F_{ij}\left[\epsilon\left(d_{ijt}, \ldots\right)\right]$.

These are combined into the log-likelihood function:

(7)

$$\begin{aligned}\ln L(\Theta) = \textstyle\sum_i \sum_t \sum_{j \in S_t \cap G_i} \quad & 1_{\{\text{call placed}_{ijt}\}} \ln\left(F_{ij}\left[\epsilon\left(d_{ijt} + 1, p_t, \phi_{it}, \phi_{jt}\right)\right] - F_{ij}\left[\epsilon\left(d_{ijt}, p_t, \phi_{it}, \phi_{jt}\right)\right]\right) \\ & + \left[1 - 1_{\{\text{call placed}_{ijt}\}}\right] \ln F_{ij}\left[\epsilon\left(1 \text{ second}, p_t, \phi_{it}, \phi_{jt}\right)\right]\end{aligned}$$

The full sample has 1,525,061 nodes, 414.5 million links, and a total of 15 billion link-month duration observations. The calling decision has 7 types of parameters. I assume that the shape and sensitivity parameters are common to all links (γ, α, β_{cost}, $\beta_{coverage}$). I allow the parameter scaling the shock distribution (σ_i), and the probability of no call at any price $(1-q_i)$ to vary at the individual level. I allow the shock distribution to be shifted at the link level, with structure:

$$\mu_{ij} = \mu_i + \mu_{\max(x_i,x_j),\overline{\phi_{it}\phi_{jt}}}$$

which includes an individual mean term μ_i, and a cost fixed effect for each combination of link adoption date $(\max\{x_i, x_j\})$ and average coverage $(\overline{\phi_{it}\phi_{jt}})$, discretized to 519 combinations. This term ensures that price and coverage sensitivity are identified off of within-link changes in calling.[32]

Bjorkegren (2018) uses a two step maximum likelihood procedure to estimate all 4.6 million parameters, exploiting the fact that conditional on the common parameters and cost fixed effects, an individual's distribution parameters affect only his own likelihood.

Adoption decision. The adoption decision bounds an individual's type under the incumbent, η_i^0. Consider the utility i would have received had he adopted a different month. At time x_i, i bought a handset rather than waiting K months. Holding fixed the actions of others, Equation 5 implies $E_{x_i}U_i^{0,x_i}(\boldsymbol{x}_{G_i}, \mathbf{0}) \geq E_{x_i}U_i^{0,x_i+K}(\boldsymbol{x}_{G_i}, \mathbf{0})$. This implies that the expected utility of being on the network during the following K months must have exceeded the expected drop in handset prices:[33]

$$\sum_{s=0}^{K-1} \delta^s E u_{ix_i+s}(p_{x_i+s}, \boldsymbol{\phi}_{x_i+s}, \boldsymbol{x}_{G_i}, \mathbf{0}) + (1-\delta^K)\eta_i^0 \geq p_{x_i}^{handset} - \delta^K E_{x_i} p_{x_i+K}^{handset} \tag{8}$$

Similarly, i could have purchased a handset earlier. At time $x_i - K$, i chose to wait, so he must have preferred some future adoption date: for some $\tilde{K} > 0$, $E_{x_i-K}U_i^{0,x_i-K+\tilde{K}}(\boldsymbol{x}_{G_i}, \mathbf{0}) \geq E_{x_i-K}U_i^{0,x_i-K}(\boldsymbol{x}_{G_i}, \mathbf{0})$. He must have valued those $\tilde{K}$ months of expected utility less than the expected drop in handset prices:

[32] To see how this formulation addresses the selection issue, note that the numerator inside the standard normal CDF in $F_{ij}[\epsilon(d)]$ can be written: $\ln\left(d^{\gamma-1}+\alpha\right) - \ln\left(1-\beta_{cost}\left(p_t + \beta_{coverage}\phi_{it}\phi_{jt}\right)\right) - \mu_{ij}$. Consider the decomposition $\mu_{ij} = \mu_i + e_{ij}$ where μ_{ij} is the true link mean and e_{ij} is an error. If the estimated specification only includes μ_i, and if e_{ij} is correlated with p_t or $\phi_{it}\phi_{jt}$, then estimates of β_{cost} and $\beta_{coverage}$ may be biased. While each link faces the same price series over time, links that join the network later face lower prices on average: the price path faced by a link is summarized by the link's adoption date. Each link faces a different coverage path; I approximate these with the average joint coverage using 10 bins.

[33] The model implies that i correctly forecasts the first K months of utility and his expectation of the continuation flow does not change between x_i and $x_i + K$. Both options provide the same continuation flow of utility after $x_i + K$, so they differ only in the utility provided in the first K months.

(9)

$$\sum_{s=0}^{\tilde{K}-1} \delta^s E u_{i,x_i-K+s}(p_{x_i-K+s}, \boldsymbol{\phi}_{x_i-K+s}, \boldsymbol{x}_{G_i}, \mathbf{0}) + (1-\delta^{\tilde{K}})\eta_i^0 \leq p_{x_i-K}^{handset} - \delta^{\tilde{K}} E_{x_i-K} p_{x_i-K+\tilde{K}}^{handset}$$

These inequalities imply bounds for each individual's type under the incumbent: $\underline{\eta}_i^0 \leq \eta_i^0 \leq \bar{\eta}_i^0$, where:

(10)

$$\underline{\eta}_i^0 = \frac{1}{1-\delta^K}\left[p_{x_i}^{handset} - \delta^K E_{x_i} p_{x_i+K}^{handset} - \sum_{s=0}^{K-1} \delta^s E u_{i,x_i+s}(p_{x_i+s}, \boldsymbol{\phi}_{x_i+s}, \boldsymbol{x}_{G_i}, \mathbf{0}) \right]$$

$$\bar{\eta}_i^0 = \max_{\tilde{K}>0}\left[\frac{1}{1-\delta^{\tilde{K}}}\left[p_{x_i-K}^{handset} - \delta^{\tilde{K}} E_{x_i-K} p_{x_i-K+\tilde{K}}^{handset} - \sum_{s=0}^{\tilde{K}-1} \delta^s E u_{i,x_i-K+s}(p_{x_i-K+s}, \boldsymbol{\phi}_{x_i-K+s}, \boldsymbol{x}_{G_i}, \mathbf{0}) \right]\right]$$

I set $K = 2$ months.[34] Note that the future after $x_i + \max(K, \tilde{K} - K)$ cancels out of these expressions: as long as the next preferred adoption date occurs within the data, results are not sensitive to the evolution of the network beyond that point. These conditions are necessary for equilibrium and are valid in the presence of multiple equilibria. During months that extra fees were charged, I incorporate the fee schedule.[35] I set the discount factor to the inverse of the average real interest rate in Rwanda over this period: $\delta = (\frac{1}{1.07})^{1/12} \sim 0.9945$ (source: World Bank). I am able to recover η_i^0's for 0.8m nodes adopting between $x_i \in [K, T-K]$.[36]

Validation. As a robustness check, Bjorkegren (2018) tests whether the value implied by calls corresponds with the value implied by adoption. I form Equations 8 and 9 into moment inequalities. I use instrumental variables that shift adoption based on the cost of providing coverage to different areas due to Rwanda's hilly geography, in

[34] I select K to balance two forces: lower values produce tighter bounds; higher ones smooth any shocks around their adoption date that are unaccounted for.

[35] Before June 2007, subscribers needed to add roughly \$4.53 in credit per month to keep their account open; I factor this in as a hassle cost. Actually opening an account entails purchasing a SIM card, which cost roughly \$1 itself plus the cost of an initial top up. See Supplemental Appendix of Bjorkegren (2018).

[36] I do not back out bounds for roughly 40,000 individuals receiving a rural handset subsidy in 2008 (for whom it is difficult to value the purchase), and whose activation does not coincide with the adoption of a new handset (altogether these account for 5% of last period durations). In simulations, I compute changes in the call model for all nodes, and hold the adoption of these fixed; doing so will tend to attenuate the results of policy counterfactuals.

a manner similar to Yanagizawa-Drott (2014), as well as in the fraction of contacts who join in response to a government adoption subsidy program. Results suggest these valuations of calls and adoption are consistent under $w = 0$ (consumers value one dollar of call utility between \$1.02-1.17 of handset price), but under $w = 1$, the utility of calls is double counted. I proceed with $w = 0$ as the base specification.[37]

Consumer decisions with multiple operators. Behavior under monopoly provision reveals how individuals trade off access to links, prices, and coverage, which would be sufficient to model choice under a basic form of competition. However, Rwanda did later add an entrant. The Supplemental Appendix assesses the extent to which the model matches behavior observed under competition in Rwanda and in similar countries that were competitive at this time. To estimate the costs of switching, and idiosyncratic preferences for the entrant, I posed hypothetical questions in a survey of mobile phone owners in Rwanda (see Supplemental Appendix for details).

Consumers find it a hassle to switch operators, especially when a switch entails changing phone numbers. Based on an incremental switching exercise, I estimate a switching cost of $s = \$36.09$, corresponding to 6.8 months of household average airtime spending in 2010 (EICV). To assess the quality of hypothetical responses, I ask respondents to make an additional hypothetical choice that is analogous to a choice observed within my data. The estimated costs of switching between plans on the same operator derived from data and from hypothetical responses do not differ significantly at the 1% level.

Consumers have a very slight idiosyncratic preference for the incumbent, holding fixed prices and coverage. I isolate this preference with an incremental switching exercise, which finds a difference with mean $m(\eta_i^0 - \eta_i^1) = \$2.45$ (\$0.01 per month), and standard deviation $\sigma(\eta_i^1 - \eta_i^0) = \$6.72$. These preferences are not correlated with observables, and when asked to explain their choices, the most common response was a preference for one operator's branding or color scheme. In counterfactual simulations, I treat these differential preferences as random parameters: for each individual I draw $e_i \overset{iid}{\sim} N\left[m(\eta_i^0 - \eta_i^1), \sigma(\eta_i^1 - \eta_i^0)\right]$, and compute his type under the entrant $[\underline{\eta}_i^1, \bar{\eta}_i^1] =$

[37]Bjorkegren (2018) finds that results do not differ substantially for several monopoly counterfactuals under the assumption $w = 1$; I do not test this in this paper because it would double very long computation times.

$[\underline{\eta}_i^0 - e_i, \bar{\eta}_i^0 - e_i]$. To reduce the computational burden, I present results drawn from a single random seed; in a robustness test in the Supplemental Appendix, I find that the random draw has little effect on outcomes.

Firm costs. I infer firm costs from two studies commissioned by the Rwandan regulator.

I infer incremental costs $ic^Y_{L_i,onnet_{ij}}$ and fixed costs fc^F from PwC (2011), a confidential cost study commissioned to set interconnection rates.[38] This study constructs a detailed engineering breakdown of the network, using cost estimates obtained from operators and crosschecked against international benchmarks. It combines the costs of towers, switching equipment, staff, central operations, and capital to compute the Long Run Incremental Cost (LRIC) of sending or receiving an additional second of voice calls. I break down these costs to better match my setup, in three ways. First, the study inflates the incremental cost estimates with a proportional markup to cover fixed costs of operating the network. I report these fixed costs separately, by multiplying each firm's total incremental cost by the same proportional markup used in the study (50%) after identifying the size of the firm in equilibrium.[39] Second, I separate out the license fee paid to the regulator, lc^F, which represents a pure transfer. (The government charged the entrant \$4m per year to operate its network when it did enter.) Third, I separate out the cost of rural tower investments. In urban areas, towers tend to be capacity constrained so that the number of towers scales with call volumes; however, in rural areas, the number of towers scales instead with coverage. For subscribers who primarily use urban towers ($L_i = urban$), I include the cost of towers in incremental costs. For subscribers who primarily use rural towers ($L_i = rural$), I compute the cost of towers separately.

I infer the annualized cost of building and operating a rural tower, K_{rural}, from RURA (2011), a study commissioned to set the regulated prices of infrastructure sharing based on cost data from operators.[40]

[38] Because this study is confidential, I am unable to report the cost estimates.

[39] Because the incumbent's fixed cost is constant across counterfactuals, only the entrant's fixed cost is relevant for evaluating the welfare gains from competition.

[40] Building a tower costs approximately \$130,000; I consider the total cost of ownership to operate a tower, which includes operating expenses, annualized depreciation, and a 15% cost of capital. Calculated depreciation assumes lifespans of 15 years for towers, 8 years for electric grid access, and

(See Supplemental Appendix for more details. In a robustness check, I find that given these cost estimates, the monopolist's chosen prices are profit maximizing in the absence of competition.)

6. Simulation

Assumptions. To make simulation tractable, I impose several restrictions. These restrictions are feasible competition rules that could be imposed by the regulator, so my results will represent a lower bound of the possible welfare gains from adding a competitor.

Operators cannot charge different prices for on- and off-net calls ($p_t^{F,G} \equiv p_t^{F,G'}$). If alternately, both firms offered low on-net charges and high off-net charges, the number of equilibria proliferates: there may be one equilibrium where all consumers subscribe to the entrant, and another where all subscribe to the incumbent. I do not have enough information to discipline the selection of equilibria under those conditions. While a rule to restrict off-net prices was not common in African markets at this time, it has been proposed for Rwanda (Argent and Pogorelsky, 2011), and has been used in several countries in an attempt to discipline competition (including Kenya, Singapore, Colombia, Turkey, Slovenia, and Portugal; see TMG (2011)).

No multihoming. In markets where different operators have low on-net prices and high off-net prices, it can be common for consumers to hold accounts with multiple operators to connect with others on different networks. Given that I restrict off-network pricing, there is less reason for consumers to hold multiple accounts. For simplicity I rule out that possibility.

At most one switch. To ease computation, I allow individuals to switch operators at most once.

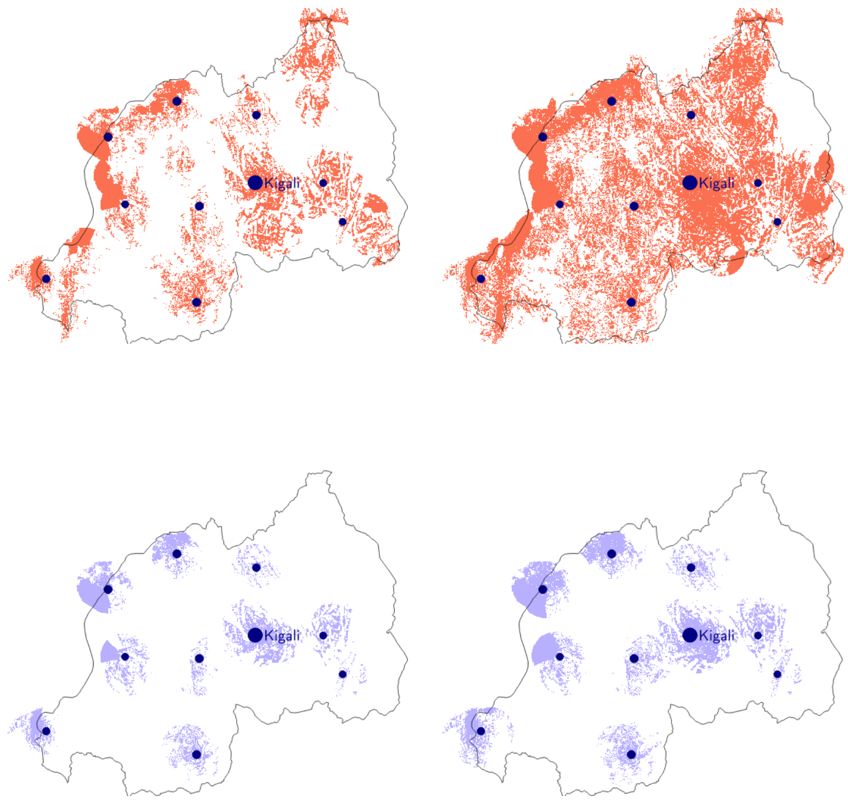
4 years for generators. This results in a total annualized cost of owning and operating a tower in Rwanda of $51,000 per year, plus $29,584 for towers that are far from the electric grid that must be powered by generators.

FIGURE 3. Rollout Plans

2005 | 2009

Observed Incumbent Rollout $\mathbf{z}_{full}$

No Rural Expansion $\mathbf{z}_{urban}$



Firm strategy space. I allow firms to set price paths as a multiple of the initial monopolist price path: $\mathbf{p}^F \in \psi \cdot \mathbf{p}^{monopoly}$, where ψ is chosen from a grid.

I assume the entrant builds only urban towers $\mathbf{z}^1 = \mathbf{z}_{urban}$, mimicking its initial entry plan (see Figure 3).[41] I allow the incumbent to adjust its rollout plan $\mathbf{z}^0$ from a menu of options defined later.

Simulation algorithm. I simulate equilibria $\boldsymbol{\Gamma}(\boldsymbol{\eta}, \boldsymbol{f}, \tilde{T})$ in two nested steps.

Firm choices. I assume that firms know the communication graph, and consumers' types (η_i^0, η_i^1) up to the estimate I measure (which is either an upper or lower bound),

[41]Operator C's global Annual Report in 2010 suggests an urban focus: 'urban centers currently represent the significant majority of the addressable population and we believe that the right approach to reaching more rural areas is increasingly to share network infrastructure with other operators.' Tower sharing in Rwanda was limited until it was mandated by the regulator in 2011.

and anticipate whether consumers will coordinate on a high or low network adoption partial equilibrium.

I consider a grid of potential regulator and firm choices (interconnection terms, and price and rollout paths: $\{(\boldsymbol{f}, \mathbf{p}^0, \mathbf{p}^1, \mathbf{z}^0, \mathbf{z}^1 | \boldsymbol{\eta}^0, \boldsymbol{\eta}^1)\}$). I identify an ε-equilibrium on this grid by allowing each firm to iteratively best respond to each other's strategy: conditioning on the decision of $-F$, firm F selects $\mathbf{p}^F$ and $\mathbf{z}^F$ to maximize profits through $\tilde{T}$, anticipating how consumers will adopt and use phones. This grid of prices approximates a continuous surface; to ease the computational burden, I first find an equilibrium on a coarse grid, and then iteratively refine the grid near that equilibrium.[42] Best responses can sometimes cycle locally around a small neighborhood; I terminate the algorithm once neither firm would profit more than $\varepsilon = \$2m$ by deviating. If the algorithm discovers multiple ε-equilibria, I report the one for which any profitable deviation is smallest. (See Appendix A for the implementation of the algorithm.)

Consumer choices. Conditional on firm and government choices, I compute a network adoption partial equilibrium $(\mathbf{x}, \mathbf{a})$ using a two step iterated best response method. I bound equilibria by exploiting their lattice structure: i's optimal adoption date x_i is weakly monotonic in his type $\boldsymbol{\eta}_i$, contact's adoption date x_j, and contact's coverage $\phi_j^{a_j}$.[43]

In the monopoly case (Bjorkegren, 2018), or when one firm is weakly better for all consumers, equilibria can be bounded simply. The lower bound of the equilibrium with lowest possible adoption, $\underline{\Gamma}$, can be identified by setting each individual's type $\boldsymbol{\eta}_i$ to its lower bound, and initializing the best response algorithm with a complete delay of adoption ($x_i^0 = \bar{T}$) with the operator with worst coverage. The upper bound of the highest possible equilibrium, $\bar{\Gamma}$, can be identified by setting each individual's

[42] I start with a grid spaced in increments of 20 percent of the monopoly price, then reduce to 10, and 5. If firms are allowed to select coverage, I allow them to do so at the finest grid level. Because I trace out a large set of conditions $\boldsymbol{f}$ and $\tilde{T}$ that induce equilibria in different parts of the grid, I end up evaluating most of the grid finely (see normal form game boards in Appendix and Supplemental Appendix).

[43] A higher type η_i^a weakly decreases i's optimal adoption date, and a decrease in i's adoption date x_i or coverage $\phi_i^{a_i}$ weakly decreases j's optimal adoption date. This follows from the lattice structure of $\boldsymbol{x}$ and because $U^{x_i}(\eta_i, \boldsymbol{x}_{-i}, \boldsymbol{\phi}_i)$ has increasing differences in x_i and x_j, or is supermodular in $\boldsymbol{x}$; see Topkis (1978) and Milgrom and Shannon (1994).

type to its upper bound, and initial choice to adopt immediately ($x_i^0 = 0$) with the operator with best coverage.

However, when firms are differentiated in two dimensions, the lattice structure can bend. j's choice of operator affects both his adoption date (x_j) and coverage ($\phi_j^{a_j}$), which can have diverging effects on the rest of the network. An individual who switches to a lower priced operator may adopt earlier but have worse coverage; this may make the network more desirable for some contacts and less desirable for others. I compute approximate bounds with a two step method. First, I compute the *quasi*equilibrium that would result from combining the most (least) attractive envelope of coverage and prices offered by the two firms, which is monotonic and represents an upper (lower) bound. Second, I start from that quasiequilibrium to compute the adoption equilibrium in the actual prices and coverage.

On occasion, there remain slight nonmonotonicities which result in a cycle; if a cycle is small, I end the algorithm and consider the result an approximate equilibrium.[44] In a bounding exercise in the Supplemental Appendix, I find that the impact of these nonmonotonicities is small.

Computing a single partial equilibrium takes about 15 hours on a supercomputer, so that computing the roughly 1,800 partial equilibria used in this paper takes approximately 1,125 supercomputer days.[45]

Dark network. If part of the dark network would have become activated prior to $\tilde{T}$, my approach will underestimate demand. I use a later representative survey (RIA, 2012) to model the behavior of the dark network nodes, and report main competition results under a shorter horizon under which these nodes would not become active. (See Supplemental Appendix. I also find similar results under a range of different horizons.)

[44]If fewer than 60 nodes are shifted for at least 10 iterations.

[45]To improve computational performance, I reoptimize nodes in parallel, with a synchronized record of all consumers' current choices. A given node is reoptimized only if its conditions or neighbors have changed (breadth first). I use secure computation nodes each with 340GB of RAM and 20 processors, housed at Brown University.

7. Monopoly Benchmarks

Before simulating a competitive equilibrium, I demonstrate how a monopoly model can diagnose how competition may affect the network. I hold fixed individuals' operator choices ($a_{it} \equiv 0$), and trace the impact of prices on welfare, and how the revenue from building rural towers is distributed across the network. These diagnostics can be computed under fewer assumptions about an eventual competitor. For simplicity, I report results under the full horizon of the data (January 2005-May 2009).

Results are shown in Table 3. At baseline during this period, the incumbent's mobile phone system provides net social welfare of $431-483m, an amount equivalent to 3% of Rwandan GDP over the same period.

Lowering prices has large welfare benefits. Anticipating that competition may induce the incumbent to lower prices, I simulate the equilibria that would result if the monopoly were to charge the price that it charged after Operator C entered in 2010: an immediate drop in calling prices of 77% (see Figure 2). I assume the firm holds this nominal price constant, and expands coverage as in the baseline. This price reduction would have lowered firm and government revenues, and due also to the cost of operating a larger network, substantially reduced firm profits. However, it would have generated huge utility benefits, more than doubling the surplus accruing to consumers. On net, social welfare would have increased by $277m (low equilibrium) or $272m (high), which corresponds with 1.6-1.7% of GDP or 8-9% of official development aid over this time period. Since results through T do not include benefits to the dark network, this is represents a lower bound. I decompose the effect into the proximal effect: allowing subscribers to individually reoptimize their usage and adoption holding fixed the adoption of others; and then any additional network effects as the impact of these decisions ripple through the network. Most of the welfare improvement comes from proximal effects; 11-19% comes from network ripple effects.

Investment in rural towers generates network spillovers. I estimate the scope for competition to affect investment by decomposing the revenue generated by the construction of rural towers.

Urban areas tend to be more lucrative, and thus profitable to serve even in the presence of competition (population densities are high and operating costs are lower). On the other hand, rural areas may be profitable to serve only if one also has a monopoly over urban areas. If market share in urban areas is split between competitors, two forces lower the returns on investing in a rural tower. First, if firms are not able to charge different prices to rural and urban areas, price pressure in the urban area can lower the revenue earned from rural calls. Second, some of the revenue will spill into the competing network.

I simulate the effects of building full baseline coverage relative to a counterfactual where only urban towers are built (see Figure 3 for coverage maps). I impose the relevant rollout plan, compute corresponding coverage, allow each consumer to adjust their adoption and calling behavior, and compute resulting equilibrium revenues and utility. I compute first the proximal effect, and then any additional network ripple effects.[46]

First, I simulate the impact of removing the full rural expansion ($\mathbf{z}^0 = \mathbf{z}_{urban}$), holding prices fixed at the monopoly level. As shown in Table 3, while only rural areas received improved coverage, rural-rural links generated only 28% (24%) of revenue. 31% (29%) of revenue came from links between rural and urban areas, and 44% (48%) came from increased calling along urban-urban links. If the network were split, the incumbent would internalize only a fraction of these urban components of the incremental revenue.

I further decompose urban-urban revenue into two parts:

Proximal benefits account for the majority of urban-urban revenue (92% or 75%): some urban consumers make calls from rural areas and thus directly benefit from rural coverage (which would be factored into their coverage measure ϕ_{it}^a). These consumers would create an incentive for the operator to compete on the quality of rural coverage.

Spillover benefits account for the remainder (8% or 25%): these can result from even consumers who have no desire to call or use rural coverage. These benefits accrue to the interior of the urban network, so would only partially be internalized

[46]Since this counterfactual makes the network less attractive, these results will be unaffected by the dark network.

if that network were split. Standard interconnection charges at the boundary of the networks would not help the incumbent internalize this revenue.

While the rural expansion was profitable at monopoly prices, if the monopoly were forced to reduce prices to the eventual competitive price, incentives to build out the entire rural network are substantially lower (and negative), as shown in the final rows of Table 3.

These simulations suggest that competition has the potential for large welfare impacts but may impact investment.

8. The Effects of Competition

This section presents the results of simulations with competition. The entrant and incumbent simultaneously submit plans; and then, consumers simultaneously choose adoption dates, operators, and usage. I compute results up to horizon December 2008 (which under a model of the dark network would not be affected by the omission of dark nodes for prices as low as 20% of the monopoly price; see Supplemental Appendix). Firms are not required to share tower infrastructure but are required to interconnect subscribers. Results tables omit fixed costs, which I estimate to lie between \$1-8m for the entrant and are included in welfare estimates in the text. Results also omit license fees, which represent transfers to the government.[47] I first fix the incumbent's coverage at the government mandated level ($\mathbf{z}^0 = \mathbf{z}_{full}$), and then consider whether it would have incentives to deviate.

Competition does not develop without government intervention. First, I allow the incumbent to dictate the terms of interconnection (f_{ij}), as is the case with most emerging network goods. Prior to the pricing game, the incumbent selects from a menu of interconnection rates ranging from \$0.00 to \$0.43 per minute. I then compute the resulting equilibrium prices and outcomes. When given the option, the incumbent will set interconnection rate to the highest value: \$0.43. The incumbent continues to charge the monopoly price, and the entrant charges 80% of the monopoly price; outcomes do not differ substantially from the monopoly case, as shown at the top

[47] Competition could reduce the fee it is feasible to charge the incumbent.

TABLE 3. Benchmark Monopoly Simulations (million $, January 2005-May 2009)

	Consumer Surplus	**Gov. Revenue**	**Firm Profits**	**Firm Revenue**				
					By Connection			
	All links	All links	All links	All links	Rural-Rural	Rural-Urban	Urban-Rural	Urban-Urban
Baseline	**[244, 270]**	**[65, 73]**	**[122, 140]**	**[165, 187]**	[30, 33]	[17, 18]	[24, 28]	[95, 108]
Impact:								
Charge eventual competitive price	**+330, +338**	**-2, -4**	**-51, -62**	**-20, -31**	**-4, -5**	**-4, -5**	**-1, -4**	**-11, -18**
... only proximal effect	+288, +316	-7, -9	-58, -67	-32, -39	-5, -6	-5, -6	-3, -5	-18, -22
... additional ripple effects	+42, +22	+5, +4	+7, +5	+12, +8	+2, +2	+1, +1	+2, +1	+7, +4
No rural expansion	**-81, -92**	**-11, -14**	**-19, -27**	**-32, -42**	**-9, -10**	**-4, -4**	**-6. -8**	**-14, -20**
... only proximal effect	-77, -83	-10, -11	-17, -21	-30, -35	-8, -9	-4, -4	-6, -7	-12, -15
... additional ripple effects	-3, -8	-1, -2	-2, -6	-2, -7	-0, -1	-0, -0	-0, -1	-1, -5
Charge eventual competitive price and no rural expansion	**+198, +217**	**-10, -11**	**-56, -66**	**-42, -49**	**-10, -10**	**-7, -7**	**-5, -7**	**-20, -25**
... only proximal effect	+155, +200	-14, -14	-62, -69	-53, -55	-10, -11	-7, -8	-7, -8	-28, -28
... additional ripple effects	+43, +17	+4, +3	+7, +3	+12, +6	+1, +1	+0, +0	+2, +1	+8, +4

of Table 4.[48] This mimics the outcomes observed in many emerging network goods, where one firm is dominant and interconnection does not arise (Katz and Shapiro, 1985).

If the firms coordinated to select an interconnection rate to maximize joint profits, they would select the same high interconnection rate of \$0.43 which stalls competition, with outcomes in Table 4. This is reminiscent of theoretical results that suggest that if firms select the interconnection rate, they may use it as an instrument of collusion to sustain high prices (Armstrong, 1998; Laffont et al., 1998).

Adding a competitor under regulated interconnection can dramatically lower prices. If interconnection terms are set to the recommended level presented to the regulator (PwC, 2011), $f_{ij} = \$0.07$, the entrant gains more by drawing away customers. The entrant would set prices to 35% of the monopoly level, and the incumbent would reduce prices to 45% of the monopoly level, charging a premium for its better quality network. Tables A1 and A2 show the resulting normal form games. Outcomes are shown in Table 4, and the price series is shown in Figure 2.

This policy change would have had an enormous impact on welfare. Over the horizon from 2005-2008, at baseline the monopoly provided a social surplus of \$334m (lower) or \$386m (upper), corresponding with 2-3% of Rwanda's GDP over the same time period. Adding a competitor under this interconnection rate would increase net social welfare by \$200m (lower) or \$208m (upper), equivalent to 1.4% of GDP or 6-7% of official development aid in Rwanda over the same period.

In this equilibrium, the entrant earns slightly negative profits. This suggests that sustaining this market structure may require subsidizing the entrant on the order of \$8m (4% of the total welfare generated), or the promise of an acquisition or additional future profits as the network grows. (In 2018, this entrant was acquired by the firm

[48]The entrant is obliged to connect to the incumbent's network, and because of the regulatory restriction that operators charge the same prices for on- and off-net calls, it cannot separately pass through the high cost of interconnection. As a result, the entrant has little advantage to drawing away customers: it pays higher than cost to interconnect with the incumbent's network. (The incumbent earns a higher profit than under monopoly: it captures rents from the entrant, which charges different prices (allowing price discrimination between urban and rural consumers), and for which some consumers have idiosyncratic preferences.)

that replaced the ineffective competitor, returning the market from a triopoly to a duopoly.)

The Supplemental Appendix reports heterogeneity in results: the entrant captures revenue in urban centers but pays out interconnection charges for calls to rural areas; the incumbent loses revenue in the urban network. Most of the benefits go to urban consumers; but proportionally most gains accrue to new subscribers and rural subscribers who benefit from the incumbent's price reductions.

The interconnection rate acts as a dial on the level of competition. Figure 4 shows equilibrium outcomes as a function of the interconnection rate (shown decreasing with the x-axis) for rates near the government recommended rate.[49] Adding a competitor under high interconnection rates results in outcomes similar to monopoly. When the incumbent is required to build rural coverage, as the interconnection rate is decreased, equilibrium prices decline, incumbent's profits decline, entrant's profits increase, and consumer surplus increases.

Increasing competition can increase incentives to invest in rural towers. I next consider whether the incumbent would alter investment in rural towers in response to competition. Determining the exact profit maximizing rollout is computationally infeasible, so I simulate suggestive counterfactuals, where the incumbent may trim back marginal, low revenue towers in response to entry.

I consider several possible rollout plans: $\mathbf{z}^0 \in \{\mathbf{z}_{full}, \mathbf{z}_{(10)}, \mathbf{z}_{(50)}\}$. I first rank each tower z by a proxy of how desirable it was for the firm to build: its average monthly empirical revenue at baseline ($\bar{R}_z$). I propose several cutoffs n and compute the progression of coverage omitting this set of rural towers ($\mathbf{z}_{(n)} = \{z \in \mathbf{z}_{full} | \bar{R}_z > \bar{R}_{(n)}$ or z is urban$\}$, where $\bar{R}_{(n)}$ is the nth order statistic of $\bar{R}$ for rural towers). For each set of prices and counterfactual rollout plans (see Appendix Figure A1), I compute each individual's time series of coverage $\phi_{it}(\mathbf{z}_{(n)})$, the resulting link utilities and durations, and then simulate a new network adoption partial equilibrium. The change in coverage has an immediate effect on calls: lower coverage increases the hassle cost of placing a call, reducing durations and the utility from calling. Consumers who

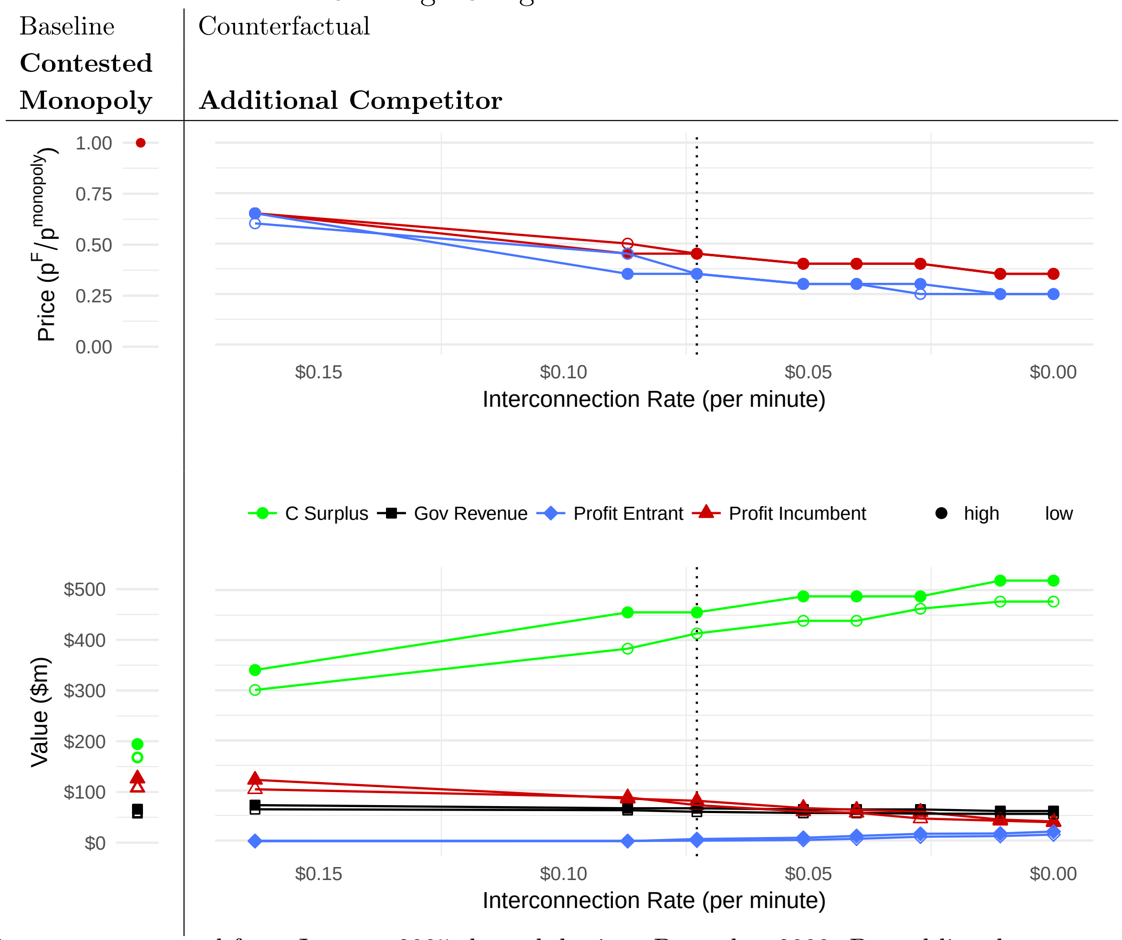
[49]There are some interconnection rates in this range that do not lead to an ε-equilibrium for this grid resolution and $\varepsilon \leq$\$2m. I omit these from the plot.

TABLE 4. Impact of Adding Competitor under Different Rules, under Incumbent Coverage Obligation

Policy			Outcomes (January 2005-December 2008)							
	Inter-connect	Switch. Cost	Prices		Incumbent		Entrant		Gov.	Consumer
					Revenue	Profit	Revenue	Profit	Revenue	Surplus
	f_{ij}	s	$\frac{\mathbf{p}^0}{\mathbf{p}^{mono}}$	$\frac{\mathbf{p}^1}{\mathbf{p}^{mono}}$						
	$/min	$			$m	$m	$m	$m	$m	$m
Baseline: Contested Monopoly	-	-	1.00, 1.00	-	[141, 164]	[108, 126]	[0, 0]	[0, 0]	[58, 66]	[168, 194]
With additional competitor...					**Impact:**					
Entering January 2005										
Interconnection rate										
...incumbent profit maximizing	0.43	36	1.00, 1.00	0.80, 0.80	-13, -3	+14, +28	+8, -3	+7, -5	-1, -2	+8, +11
...initial proposed level (RURA, 2006)	0.09	36	0.50, 0.45	0.45, 0.35	-4, -29	-22, -43	+4, +13	-1, -1	+2, -1	+215, +261
...**revised glide path start** (PwC, 2011)	0.07	36	0.45, 0.45	0.35, 0.35	-23, -33	-38, -47	+11, +17	-0, +3	-1, -1	+245, +261
...revised glide path end (PwC, 2011)	0.04	36	0.40, 0.40	0.30, 0.30	-37, -50	-53, -65	+16, +24	+4, +9	-3, -4	+271, +293
...bill and keep	0.00	36	0.35, 0.35	0.25, 0.25	-54, -72	-72, -88	+26, +34	+12, +18	-5, -7	+309, +325
...asymmetric	0.07 to incumbent 0.06 to entrant	36	0.45, 0.45	0.35, 0.35	-22, -32	-37, -46	+10, +16	-1, +2	-1, -1	+245, +261
	0.07 to incumbent 0.04 to entrant	36	0.50, 0.45	0.40, 0.35	-15, -30	-28, -44	+11, +14	0, 0	+1, -1	+221, +261
Interconnection rate revised + number portability	0.07	19	0.45, 0.45	0.35, 0.35	-26, -37	-40, -50	+14, +20	+1, +5	-1, -2	+246, +262
Entering July 2008										
...revised glide path start (PwC, 2011)	0.07	36	0.65, 0.65	0.35, 0.35	-2, 0	-11, -11	+4, +4	+1, +1	+2, +3	+118, +133

In outcome cells, first number is outcome in low equilibrium; second in high. Profits omit fixed costs of operation and license fees.

FIGURE 4. Equilibrium Results as Function of Interconnection Rate, under Incumbent Coverage Obligation



Outcomes computed from January 2005 through horizon December 2008. Dotted line denotes implemented interconnection rate (PwC, 2011). Filled marks denote high equilibrium and open marks denote low equilibrium. Red represents incumbent and blue entrant.

obtain less utility from calling may also change their operators, or adoption decision, which can cause even consumers who were not directly affected by the change in coverage to change their decisions.

I decompose incentives to invest in Table 5, by market structure and interconnection rate. I first simulate adoption partial equilibria where tower investments are removed, and then measure the effect of adding those investments in two stages: first, if consumers can change adoption dates and usage but not operators, and if consumers can also change operators (thus capturing incentives for operators to differentiate).

I first consider the incentives to build the 50 lowest revenue rural towers, which had a social return on investment (ROI) above 6.64 but a private ROI of 0.98-1.00 under monopoly. The net effect of competition policy on investment arises from three forces, decomposed in Table 5 and below for the government recommended interconnection rate of \$0.07/minute:

1. Competition lowers overall revenues. Because price discrimination is limited, when the incumbent faces competition in the urban market, it lowers prices across the whole network. As a result, each second of talk time generates less revenue. Under monopoly, building these towers generated a total of \$2.57m (lower equilibrium) or \$2.46m (upper) of revenue. However, under competition it generated net revenue \$1.92m combined between the two operators.

2. Competition splits the revenue generated by rural towers... Under competition, not only is total revenue lower; it is now split with another firm. To see this more clearly, consider the outcomes that result when consumers can adjust adoption and usage but not operator ('fixing operator').

2a. ...some revenue accrues at the boundary of the competing network. The investment increases calls from the entrant's network to the incumbent's network, shown in the entrant's off-net column. Holding fixed operator choices, 15% of the revenue from the incumbent's investment accrues to the border with the entrant's network. These spillovers can partially be recouped with interconnection fees: 10% of total revenue is given back.[50]

2b. ...some revenue accrues to the interior of the competing network. 0.4% (lower) or 1% (upper) of the revenue generated by the incumbent's investment results from spillovers in the interior of the entrant's network–shown in the entrant's on-net column. Since interconnection fees are incurred only at the boundaries of the two networks, they do not adjust for these internal spillovers. The magnitude of these internal spillovers will depend on the shape of the entrant's network, as well as the degree of

[50]Note that theoretically, there can be cases where competition *increases* revenues from this channel: if operators are sufficiently differentiated that the entrant attracts consumers who would not have adopted under the incumbent, and interconnection fees are large enough. However, in this case, the entrant offers an inferior service that is not sufficiently differentiated.

network spillovers: they require the entrant's network to be both porous to adoption spillovers, and sufficiently deep that spillovers reach beyond the border. In this case, the entrant's network is relatively small, and these interior spillovers are also relatively small.

On net, effects 1 and 2 lower the private ROI to -0.12 (lower) or -0.16 (upper): if operator choices were fixed, competition would induce the incumbent not to build these towers.

3. A business stealing effect increases the incentive to differentiate quality. However, the bulk of revenues generated by the investment under competition arise from a business stealing motive. Although the networks are interconnected, each firm offers its own set of towers. The effect of this competitive differentiator is observed when consumers are allowed to change their choice of operator (see rows 'plus operator choice'). Because the investment is valued by subscribers who otherwise would select the entrant's network, it induces many of them to switch to the incumbent. This business stealing effect dwarfs the network effects foregone by the incumbent and internalized by the entrant. With this effect, building additional rural towers tends to reduce the entrant's revenues and profits.

With this business stealing effect, the private ROI of these rural towers rises to 1.10 (lower) or 1.15 (upper): larger than the returns under monopoly.

I also evaluate the returns to building the 10 lowest revenue rural towers, which were found to be unprofitable under monopoly but built due to a government coverage obligation (Bjorkegren, 2018). Under monopoly, the private ROI was -0.61 (lower) or -0.50 (upper) despite a positive social ROI (0.63 or 0.87). Adding a competitor under the government recommended interconnection rate would have increased the private ROI to 0.31 (lower) or 0.32 (upper), which would have made it profitable to build these marginal towers even in the absence of a coverage obligation.[51]

[51]In the Supplemental Appendix I find that under a longer horizon, at the recommended interconnection rate competition increases the private ROI of building these towers but not enough to make them profitable.

In the Supplemental Appendix, I also simulate a full competitive equilibria in prices and incumbent coverage $\mathbf{z}^0 \in \{\mathbf{z}_{full}, \mathbf{z}_{(10)}, \mathbf{z}_{(50)}\}$. I find similar results: under the government recommended interconnection rate, competition would induce the incumbent to build these last 10 towers even in absence of the obligation.[52]

However, whether competition increases or decreases incentives to invest depends on several factors.

First, it depends on the interconnection rate. If the government implemented an interconnection rate of zero ('bill and keep', to which the U.S. is transitioning (FCC, 2011)), more intense competition leads to lower prices, and the incumbent does not earn interconnection fees for the benefits it provides to the other network. The private ROI of the 50 lowest revenue towers decreases below the monopoly level to 0.57 (lower) or 0.54 (upper). The ROI of the 10 lowest towers is lower than under the government recommended date, but remains above the monopoly level: 0.09 (lower) or 0.13 (upper).

Second, in general it will also depend on how preferences interact with the network. Consider an alternate case where consumers did not travel, so that rural consumers valued only rural coverage, and urban consumers valued only urban coverage. Then, the incumbent may be the only option for rural consumers, but urban consumers would not switch operators based on rural coverage. In that case there would be no business stealing effect, and competition would tend to lower incentives to invest in towers.

The monopoly benchmark simulations presented in Section 7 foreshadow that the business stealing effect is likely to be large here: a large portion of revenue generated by rural towers comes from urban consumers who value and use rural coverage. Such diagnostic simulations can be computed even in settings where later entry is not observed.

Asymmetric interconnection rates give regulators finer control. Given that interconnection rates accrue only at the border of a network, a regulator may allow a larger network to charge a higher rate to offset spillovers that would otherwise accrue to its interior. (Alternately, the regulator could tilt favor towards a smaller network

[52]See results in Normal Form Game Boards section of Supplemental Appendix.

TABLE 5. Return on Tower Investments under Different Competition Policies

	Equilibrium		Impact of Investment								ROI	
	Prices		Incumbent			Interconnect	Entrant					
	Incumb.	Entrant	Costs	Revenue		Fees	Revenue		Costs			
	$\frac{\mathbf{p}^0}{\mathbf{p}^{mono}}$	$\frac{\mathbf{p}^1}{\mathbf{p}^{mono}}$		On-net	Off-net calls	$\leftarrow$	Off-net calls	On-net			Private	Social
			\$m	\$m	\$m	\$m	\$m	\$m	\$m			
Impact of incumbent building towers 1-50												
Contested monopoly	**1.00, 1.00**	-	**1.30, 1.23**	**2.57, 2.46**	**0, 0**	-	-	-	-		**0.98, 1.00**	**6.64, 6.49**
With competitor, interconnection \$0.07/min	**0.45, 0.45**	**0.35, 0.35**	**2.70, 2.79**	**7.85, 8.27**	**-2.54, -2.70**	**0.37, 0.44**	**-1.65, -1.65**	**-1.74, -2.00**	**-1.68, -1.80**		**1.10, 1.15**	**7.85, 8.13**
...fixing operator			1.11, 1.08	0.84, 0.77	0.04, 0.04	0.10, 0.09	0.15, 0.14	0.004, 0.01	0.05, 0.05		-0.12, -0.16	5.86, 5.92
...plus operator choice			1.59, 1.71	7.02, 7.49	-2.59, -2.73	0.27, 0.35	-1.80, -1.78	-1.75, -2.01	-1.74, -1.85		-	-
With competitor, interconnection \$0	**0.35, 0.35**	**0.25, 0.25**	**2.85, 3.01**	**6.60, 6.97**	**-2.14, -2.32**	**0, 0**	**-1.13, -0.89**	**-1.53, -1.97**	**-1.84, -2.04**		**0.57, 0.54**	**7.94, 8.21**
...fixing operator			1.10, 1.07	0.64, 0.60	0.03, 0.03	0, 0	0.10, 0.08	0.004, 0.002	0.05, 0.04		-0.39, -0.41	5.75, 5.82
...plus operator choice			1.75, 1.94	5.95, 6.36	-2.18, -2.35	0, 0	-1.23, -0.98	-1.53, -1.97	-1.89, -2.08		-	-
Impact of incumbent building towers 1-10												
Contested monopoly	**1.00, 1.00**	-	**0.14, 0.14**	**0.05, 0.07**	**0, 0**	-	-	-	-		**-0.61, -0.50**	**0.63, 0.87**
With competitor, interconnection \$0.07/min	**0.45, 0.45**	**0.35, 0.35**	**0.22, 0.22**	**0.46, 0.48**	**-0.16, -0.16**	**-0.02, -0.02**	**-0.15, -0.15**	**-0.07, -0.07**	**-0.09, -0.10**		**0.31, 0.32**	**1.33, 1.37**
...fixing operator			0.14, 0.13	0.03, 0.02	0.001, 0.0009	0.005, 0.01	0.01, 0.01	0.0001, 0.00006	0.002, 0.002		-0.76, -0.80	0.97, 0.80
...plus operator choice			0.08, 0.09	0.44, 0.45	-0.16, -0.16	-0.02, -0.02	-0.15, -0.16	-0.07, -0.07	-0.10, -0.10		-	-
With competitor, interconnection \$0	**0.35, 0.35**	**0.25, 0.25**	**0.22, 0.23**	**0.37, 0.39**	**-0.13, -0.13**	**0, 0**	**-0.10, -0.10**	**-0.06, -0.06**	**-0.10, -0.10**		**0.09, 0.13**	**1.36, 1.57**
...fixing operator			0.14, 0.14	0.02, 0.02	0.001, 0.0009	0, 0	0.01, 0.01	0.00009, 0.00007	0.002, 0.003		-0.85, -0.87	0.82, 0.96
...plus operator choice			0.09, 0.09	0.35, 0.37	-0.13, -0.13	0, 0	-0.10, -0.11	-0.06, -0.06	-0.10, -0.10		-	-

In outcome cells, first number is outcome in low equilibrium; second in high. Outcomes computed from January 2005 through horizon December 2008. When holding operator choices fixed, consumers who initially switched operators are allowed to change their adoption date for the initial operator but maintain the same switch date. On-net revenues include revenue from extra fees. Interconnect fees represent net payment from entrant to incumbent. Social ROI represents consumer surplus, government revenue, and firm profit, relative to firm costs.

by allowing it discounted access to the larger network.) I consider outcomes under asymmetric interconnection rates that favor the incumbent in Table 4: these shift a small amount of profits from entrant to the incumbent.

Number portability increases the level of competition. 31% of Rwandans state that they would have switched operators if they could keep their phone number (Stork and Stork, 2008).[53] In 2013, 25% of developing markets had introduced number portability and 15% were planning to do so in the future (GSMA, 2013). However, there are concerns that forcing number portability before a market is mature may reduce investment. Rwanda initially planned to introduce portability when mobile operators reached combined 60% market penetration, but as of this writing has yet to do so.

I simulate the effect of introducing number portability in Table 4, by reducing the cost of switching operators from \$36.09 to \$18.51 (based on my consumer survey estimates; see Supplemental Appendix). I assume the interconnection rate is set to the government recommended level. This results in more consumers using the entrant, which tends to raise entrant profits (+\$1-2m relative to competition without number portability) and lower incumbent profits (-\$2-3m). This suggests that if given the choice, the incumbent would elect to maintain high switching costs. The policy results in a small boost in consumer surplus (+\$1m). In the Supplemental Appendix, I find little heterogeneity in impact between initial and later subscribers: some later subscribers take advantage of low switching costs to switch to the incumbent after its coverage improves.

Delaying entry reduces the impact of competition. I consider allowing the competitor to enter in July 2008, 5 months before the end of the horizon, under the government recommended interconnection rate. Before the entry date, subscribers may select only the incumbent ($a_{it} \equiv 0$ for $t < t_{entry}$); after that date, they may select either ($a_{it} \in \{0, 1\}$ for $t \geq t_{entry}$). Outcomes are shown in the bottom of Table 4. Relative to early entry, the entrant sets the same prices (35% of the monopoly

[53]There are similar policy options in other markets. For example, Google criticized Facebook for making it difficult to export lists of friends, thus making it more difficult to switch from Facebook to the nascent Google+ social network.

level), the incumbent keeps prices higher (65% of the monopoly level), and the total impact on welfare is muted. This is similar to the baseline case, where the Rwandan government did eventually allow in the entrant (Operator C) at the end of 2009.[54]

Robustness.

Alternate Horizons. In the Supplemental Appendix I show that results are robust under different time horizons. Results could differ if either the main horizon inadequately controls for the dark network, or if the choice of optimization horizon has a substantial impact on firm decisions. Holding coverage fixed, I find that equilibrium prices are comparable or lower, and welfare effects are comparable or larger under different horizons. Conditional on prices, any omission of dark nodes or links would lead to underestimating the incentives to invest in rural towers under competition.[55] If the main horizon inadequately controls for the dark network, my results are likely to underestimate the benefits of competition.

9. Conclusion

Societies are grappling with an increasing number of industries characterized by network effects. This paper develops a method to simulate the effects of competition policy in a network industry. I demonstrate how data from an incumbent monopoly can be used to estimate the effects of a variety of competition policies. My method captures how changes ripple throughout networks and across network boundaries, and can thus decompose how the policy environment affects incentives to invest. In addition to the policies demonstrated here, this method can also estimate effect of splitting up an incumbent, under arbitrary splits of customers and assets (while such a policy was not under consideration in my context, it is under consideration in others).

I focus my approach on an industry of particular importance to developing societies. Mobile phone networks provide the infrastructure for an increasing array of

[54] Note that in this counterfactual, the single price path that the incumbent must commit to spans both the period of monopoly and entry.

[55] Any nodes or links that I omit would benefit consumers, pushing adoption forward, and would represent additional revenue. If the firms set lower prices, that could reduce the revenue obtained from an investment, but a regulator could impose a price floor to obtain price and investment outcomes as least as beneficial as I observe here.

vital services, including communication and increasingly payments and banking. I find that competition in the Rwandan mobile phone industry has a large scope to affect welfare. I find that policies to increase competition have mixed effects on incentives to invest: they split the revenue generated by rural towers, but this effect is mostly dominated by increased returns from differentiating quality. While I focus on the primary investments in this network, in rural towers, network firms have a menu of potential investments which would be differentially affected by competition. Competition will tend to make investments that induce a marginal customer to switch more attractive, and investments that induce dispersed network spillovers less attractive. Competition is thus likely to affect the technological direction of emerging networks.

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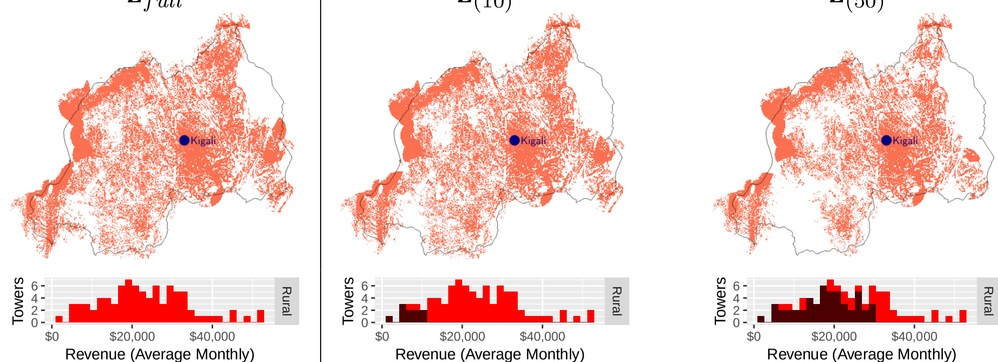
FIGURE A1. Menu of Tower Investments for Incumbent

Baseline | Counterfactuals dropping low revenue rural towers

$\mathbf{z}_{full}$ $\mathbf{z}_{(10)}$ $\mathbf{z}_{(50)}$



Coverage as of May 2009.

	10pct	15pct	20pct	25pct	30pct	35pct	40pct	45pct	50pct	55pct	60pct	65pct	70pct	75pct	80pct	85pct	90pct	95pct	Full
10pct	-22, **-2**																		
15pct	11, -18	-1, **-1**																	
20pct	27, -26	25, -13	17, **-1**																
25pct	38, -33	39, -20	37, -9	34, **-1**															
30pct	**42**, -37	46, -23	49, -14	49, -5	45, **-1**														
35pct	41, -40	**48**, -25	**52**, -14	56, -8	57, -4	57, **-1**													
40pct	37, -40	45, -26	52, -15	**58**, -7	**63**, -4	68, -2	69, **-1**												
45pct	33, -38	40, -25	48, -14	56, -6	62, -1	**71**, **-0**	77, -1	79, -1											
50pct	28, -36		41, -11	49, -3	58, 2	68, **4**	**77**, 3	**85**, 1	88, -1										
55pct			36, -8	42, 0	51, 5	62, 9	72, **9**	82, 5	**90**, 1	92, -1									
60pct			30, -5	37, 3	43, 10	54, 13	66, **14**	76, 12	86, 7	**96**, -0	97, -1								
65pct			26, -3	31, 6	37, 12	45, 18	56, **20**	68, 18	78, 14	91, 7	**102**, -0	103, -1							
70pct	17, -32				31, 16	38, 22	47, **26**	57, 25	68, 21	81, 17	95, 8	**106**, -0	107, -1						
75pct						32, 26	39, 31	47, **32**	58, 28	71, 24	83, 18	96, 8	**107**, -0	108, -1					
80pct			17, 1		23, 21	27, 29	32, 35	39, **37**	46, 36	58, 32	71, 26	85, 18	99, 8	**109**, -0	**110**, -1				
85pct													87, **18**	101, 7	109, -0	**110**, -1			
90pct	9, -29				17, 24		23, 41		32, **45**		46, 43		72, 28	87, 18	102, 6	108, -0	**110**, -1		
Full	6, -29	7, -10	9, 5		11, 27	14, 36	16, 44		22, 51	25, **54**	30, 53	36, 52	45, 47	57, 39	72, 29	87, 17	100, 6	**106**, -0	**107**, -1

Incumbent actions in rows; entrant in columns. Cells represent incumbent and entrant profits, in million USD.
Best responses are bolded. Underlined cell represents a Nash Equilibrium.

TABLE A1. Competitive Interaction: Interconnection \$0.07 Switching Cost \$36 Low Equilibrium -200812 (50pct dark)

	10pct	15pct	20pct	25pct	30pct	35pct	40pct	45pct	50pct	55pct	60pct	65pct	70pct	75pct	80pct	85pct	90pct	95pct	Full
10pct	-22, **-1**																		
15pct	13, -20	0, **-1**																	
20pct	30, -27	28, -15	20, **-1**																
25pct	41, -35	43, -21	42, -10	39, **-2**															
30pct	**45**, -39	49, -24	54, -15	55, -5	55, **-2**														
35pct	44, -42	**51**, -26	**57**, -14	64, -8	66, -2	69, **-2**													
40pct	40, -42	48, -27	57, -15	**64**, -5	**72**, -2	77, **1**	78, -2												
45pct			52, -13	62, -4	71, 2	**79**, **3**	**84**, 0	86, -2											
50pct	31, -38		45, -10	55, -1	66, 6	76, **8**	84, 4	**93**, 1	97, -2										
55pct			39, -7	47, 4	58, 9	69, **13**	79, 11	90, 7	**101**, 2	106, -2									
60pct			33, -4	40, 7	49, 15	60, **19**	71, 16	83, 15	96, 10	**108**, 3	**115**, -2								
65pct					42, 19	50, **25**	60, 22	74, 22	87, 19	102, 12	114, 4	**122**, -2							
70pct	19, -33				35, 24	42, 29	50, 29	62, **29**	77, 27	91, 22	107, 13	118, 2	**123**, -2						
75pct					30, 27	35, 34	42, 34	51, **37**	64, 36	79, 32	94, 26	107, 14	121, 1	124, -2					
80pct			20, 3		26, 29	30, 37	36, 38	43, 43	53, **44**	66, 41	82, 35	95, 26	109, 13	**125**, 0	127, -2				
85pct						26, 39	30, 42	36, 47	43, 50	53, **51**	67, 46	81, 36	96, 25	111, 13	**127**, -0	**129**, -2			
90pct	11, -30				20, 33	23, 41	26, 45	30, 51	37, 55	44, **57**	54, 56	67, 47	81, 36	97, 25	112, 11	126, -0	**128**, -2		
95pct							22, 47	26, 54	30, 59		44, **63**		66, 47	81, 36	97, 24	116, 8	125, -0		
Full	8, -30	10, -10	11, 7		14, 34	16, 44	19, 49		26, 62	30, 66	37, **68**	43, 64	52, 57	65, 47	81, 36	97, 23	116, 8	**125**, -0	**126**, -2

Incumbent actions in rows; entrant in columns. Cells represent incumbent and entrant profits, in million USD.
Best responses are bolded. Underlined cell represents a Nash Equilibrium.

TABLE A2. Competitive Interaction: Interconnection \$0.07 Switching Cost \$36 High Equilibrium -200812 (50pct dark)

Appendix A. Simulation Algorithms

The simulation algorithm can be described in three nested steps. For monopoly simulations, operator choices are held fixed at $a = 0$.

Adoption Iterated Best Response Algorithm.

Require: firm price paths $\mathbf{p}$ and coverage paths ϕ
Require: candidate adoption path $\mathbf{x}^0$ and operators $\mathbf{a}^0$

$k \leftarrow 0$
repeat
  for each individual i **do**
    for proposed adoption month $t = 0$ to $\bar{T}$ **do**
      for first operator $a = 0$ to 1 **do**
        find optimal switch point $\tilde{t}$, or if not optimal to switch, $\tilde{t} \leftarrow \bar{T}$
        $\mathbf{a}_a^* \leftarrow [\underbrace{a \quad a \quad \cdots \quad a}_{\tilde{t}\text{ elements}} \underbrace{(1-a) \quad (1-a) \quad \cdots \quad (1-a)}_{\bar{T}-\tilde{t}\text{ elements}}]$
        solve $t_a^* \leftarrow \arg\max_s E_t U_i^{\mathbf{a}_a^*, s}(\mathbf{a}^k_{G_i}, \mathbf{x}^k_{G_i})$
        $u_a^* \leftarrow E_t U_i^{\mathbf{a}_a^*, t_a^*}(\mathbf{a}^k_{G_i}, \mathbf{x}^k_{G_i})$
      end for
      $a^* \leftarrow \arg\max_a u_a^*$
      if $t = t^*_{a^*}$ **then**
        $x_i^{k+1} \leftarrow t$
        $\mathbf{a}_i^{k+1} \leftarrow \mathbf{a}^*_{a^*}$
        break
      end if
    end for
  end for
  $k \leftarrow k + 1$
until $\mathbf{x}^k = \mathbf{x}^{k-1}$ or fewer than 60 nodes shifted in each of the last 10 iterations
return iterated best response path $\mathbf{x}^k$ and operators $\mathbf{a}^k$

Network Adoption Partial Equilibrium.

Require: firm price paths $\mathbf{p}$ and coverage paths ϕ

Require: bound $\in \{\text{lower}, \text{upper}\}$

if bound = upper **then**

compute adoption iterated best response quasiequilibrium $\tilde{\mathbf{a}}, \tilde{\mathbf{x}}$ given lower envelope of firm price paths $\mathbf{p}$ and upper envelope of coverage paths $\boldsymbol{\phi}(\mathbf{z})$ starting from $\tilde{\mathbf{a}}_0 = \mathbf{0}, \tilde{\mathbf{x}}_0 = \mathbf{0}$

compute adoption iterated best response equilibrium $\mathbf{a}, \mathbf{x}$ given firm price paths $\mathbf{p}$ and coverage paths $\boldsymbol{\phi}(\mathbf{z})$ starting from $\mathbf{a}_0 = \mathbf{0}, \mathbf{x}_0 = \tilde{\mathbf{x}}$

else if bound = lower **then**

compute adoption iterated best response quasiequilibrium $\tilde{\mathbf{a}}, \tilde{\mathbf{x}}$ given upper envelope of firm price paths $\mathbf{p}$ and lower envelope of coverage paths $\boldsymbol{\phi}(\mathbf{z})$ starting from $\tilde{\mathbf{a}}_0 = \mathbf{1}, \tilde{\mathbf{x}}_0 = \bar{\boldsymbol{T}}$

compute adoption iterated best response equilibrium $\mathbf{a}, \mathbf{x}$ given firm price paths $\mathbf{p}$ and coverage paths $\boldsymbol{\phi}(\mathbf{z})$ starting from $\mathbf{a}_0 = \mathbf{1}, \mathbf{x}_0 = \tilde{\mathbf{x}}$

end if

return consumer partial equilibrium path $\mathbf{x}$ and operators $\mathbf{a}$

Full Equilibrium. The full equilibrium adaptively refines the grid near the equilibrium identified on successively less coarse grids. My main simulations impose the government coverage requirement $\mathbf{z}_0 = \mathbf{z}_{full}$; in the Supplemental Appendix I consider equilibria in prices and coverage.[56]

Require: interconnection terms $\mathbf{f}$ and tolerance ε

$\underline{r}_0, \underline{r}_1 \leftarrow 0.10$

$\bar{r}_0, \bar{r}_1 \leftarrow 1.00$

$k \leftarrow 0$

$\mathbf{p}_0^0, \mathbf{p}_1^0 \leftarrow \mathbf{p}^{monopoly}$

for Δ in $\{0.2,\ 0.1,\ 0.05\}$ **do**

repeat

for firm $F = 0$ to 1 **do**

$\mathbf{p}_F^{k+1}, \mathbf{z}_F^{k+1} \leftarrow \arg\max_{\mathbf{p}_F, \mathbf{z}_F} \pi_F(\{\mathbf{p}_F, \mathbf{p}^k_{-F}\}, \{\mathbf{z}_F, \boldsymbol{z}^k_{-F}\}, \mathbf{a}, \mathbf{x}, \boldsymbol{f})$

s.t. $\mathbf{p}_F \in \{\underline{r}_F, \underline{r}_F + \Delta, \underline{r}_F + 2\Delta, ..., \bar{r}_F\} \cdot \mathbf{p}^{monopoly}$ [57]

[56]For those simulations, to reduce the computational burden, I first refine the grid around an equilibrium in prices, and then allow for deviations in prices and coverage around that equilibrium at the finest resolution, as described in the algorithm below.

s.t. $\mathbf{z}_0 \in \{\mathbf{z}_{full}, \mathbf{z}_{(10)}, \mathbf{z}_{(50)}\}$ if $\Delta = 0.05$ else $\mathbf{z}_0 = \mathbf{z}_{full}$

s.t. $\mathbf{z}_1 = \mathbf{z}_{\text{no rural}}$

s.t. $\mathbf{a}, \mathbf{x}$ are a network adoption partial equilibrium given firm price paths $\mathbf{p}$ and coverage paths $\boldsymbol{\phi}(\mathbf{z})$

end for

until $\mathbf{p}_0^{k+1} = \mathbf{p}_0^k$ and $\mathbf{p}_1^{k+1} = \mathbf{p}_1^k$ and $\mathbf{z}_0^k = \mathbf{z}_0^{k+1}$ or reaches a cycle with a deviation that earns profits below ε. If so, break at least profitable deviation.

$\bar{r}_0 \leftarrow \frac{\mathbf{p}_0^k}{\mathbf{p}^{monopoly}} + \Delta$

$\bar{r}_1 \leftarrow \frac{\mathbf{p}_1^k}{\mathbf{p}^{monopoly}} + \Delta$

$\underline{\mathrm{r}}_0 \leftarrow \frac{\mathbf{p}_0^k}{\mathbf{p}^{monopoly}} - \Delta$

$\underline{\mathrm{r}}_1 \leftarrow \frac{\mathbf{p}_1^k}{\mathbf{p}^{monopoly}} - \Delta$

end for

return firm price paths $\mathbf{p}$ and rollout plans $\mathbf{z}$, and consumer equilibrium path $\mathbf{x}^k$ and operators $\mathbf{a}^k$

[57]Note that for a given interconnection rate, the algorithm will only actively compute candidate network adoption partial equilibria for this range of prices for a given resolution Δ. However, if network adoption partial equilibria with the same resolution have been computed for other prices for different interconnection rates, those will also be considered. As a result, results tend to be stable under a wider range of prices. See normal form game boards in Supplemental Appendix for examples of what has been computed.